SIMULATION OF BENZENE TRANSPORT AND BIODEGRADATION DURING TRANSIENT HYDRAULIC CONDITIONS

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A

THESIS

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ABSTRACT

MODFLOW and BIOMOC were used to simulate transport and biodegradation of benzene in the alluvial aquifer adjacent to the Chena River. MODFLOW was used to calculate ground water fluxes at the boundaries of the BIOMOC model, which was used to model transport and biodegradation of benzene. A benzene plume located 300 ft. southeast of the study site is superimposed onto the cross-sectional model of the study area. Only saturated zone processes were modeled. Anaerobic biodegradation was the only simulated biodegradation process. The simulation shows 0.003% of the theoretical benzene entering the saturated zone is biodegraded, 0.6% is adsorbed by solids, and 99.4% leaves the model boundaries. The simulation predicts theoretical concentrations of benzene are 2 to 8 μg/l when discharging into the river. Field data do not support this finding. Processes not simulated, such as aerobic degradation at the water table, may make significant contributions toward limiting benzene transport.

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
centimeters (cm)	$1x10^{-2}$	meter (m)

Physical and Chemical Water-Quality Units:

Temperature: Water and air temperature are reported in degrees Celsius. Degrees Celsius (°C) can be converted to degrees Fahrenheit by use of the following equation:

$$°F=1.8(°C)+32$$

Specific electrical conductance (conductivity): Conductivity of water is expressed in microsiemens per centimeter (µS/cm) at 25 °C. This unit is equivalent to micromhos per centimeter (µmho/cm) at 25 °C.

Milligrams per liter (mg/l): Milligrams per liter is a unit of measurement indicating the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water.

Vertical Datum:

In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929), a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929. All elevations were measured from the U.S. Army Corps of Engineers benchmark LFC-66A. (last surveyed in 1985, elevation 444.98 ft above sea level; Local Military Coordinates N291901.81, E303283.11)

Horizontal Datum:

The horizontal datum for all locations in this report is the North American Datum of 1927. The U.S. Army typically uses local coordinate systems for each installation. These coordinates are converted to state-plane coordinates (zone 3) and latitude and longitude.

Abbreviations used in this report:

AEC	U.S. Army Environmental Center
BLM	U.S. Bureau of Land Management
BTEX	benzene, toulene, ethylbenzene and xylene
COE	U.S. Army Corps of Engineers, Alaska District
DO	dissolved oxygen
N	normal
NGVD	National Geodetic Vertical Datum of 1929
PVC	polyvinyl chloride
TCE	trichloroethylene
TDR	time domain reflectometry
UAF	University of Alaska Fairbanks
USARAK	U.S. Army Alaska
USGS	U.S. Geological Survey
WERC	Water and Environmental Research Center

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1. INTRODUCTION

Transient hydraulic conditions significantly affect the ground water system along the Chena River, Ft. Wainwright, Alaska (Figure 1). These dynamics can influence the natural attenuation of contaminants by many processes. Natural attenuation of contaminants includes mechanisms of biodegradation, sorption, dilution, volatilization, dispersion and advection. These processes can occur simultaneously, which presents a complex system of variables to be determined. BIOMOC is a two-dimensional multispecies reactive solute-transport model which can simulate sequential aerobic and anaerobic degradation processes. BIOMOC was used to simulate benzene transport and biodegradation adjacent to the Chena River during transient hydraulic conditions.

MODFLOW is a finite-difference ground-water flow model. Nakanishi and Lilly (1998) used MODFLOW to estimate aquifer properties by numerically simulating ground water and surface water interactions at Ft. Wainwright, Alaska during 1995. This two-dimensional cross-sectional model is used to simulate the ground water and surface water interactions for 1996 through 1998. The ground water flux rates and hydrologic properties resulting from these simulations were used for BIOMOC boundary conditions. This allowed simulations of benzene transport and biodegradation in the study area. Hydrologic and geochemical data collected between 1995 and 1998 field seasons were used for model input and quality-assurance testing. Data-collection sites are located adjacent to the Chena River at Operative Unit 5, Ft. Wainwright, Alaska (Figure 2).

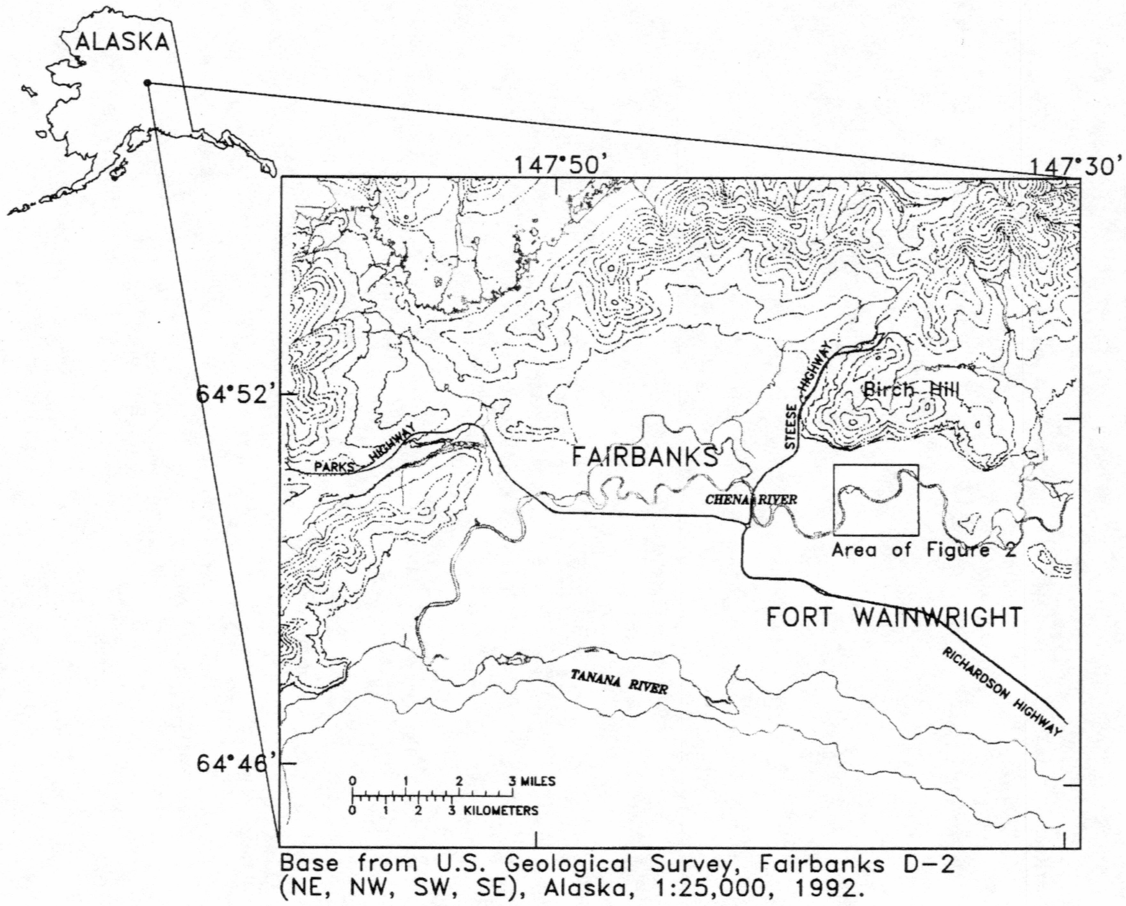


Figure 1. Location of Ft. Wainwright, Alaska.

1.1 Purpose and Scope

The purpose of this study was to interpret the effects of Chena River interactions with groundwater on the transport and biodegradation of benzene in the adjacent alluvial aquifer. The objective was to determine whether anaerobic biodegradation is a viable option for remediation of benzene contamination close to the Chena River at Ft. Wainwright. MODFLOW was used to calculate ground water fluxes in the system.

BIOMOC was used to model transport and biodegradation of benzene in the saturated zone adjacent to the river.

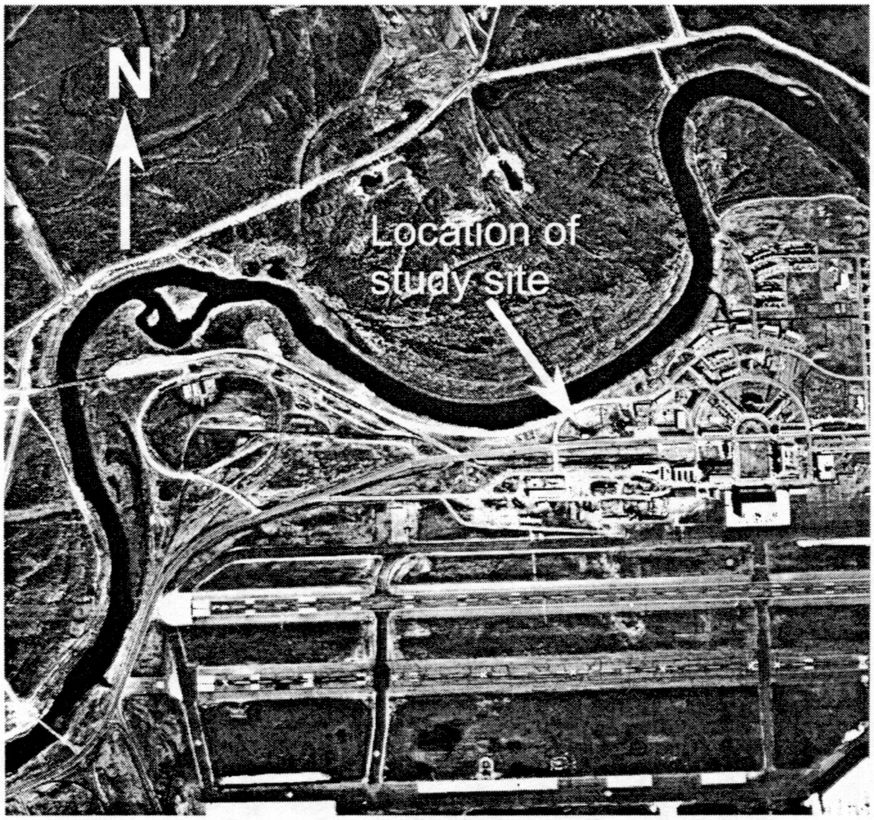


Figure 2. Aerial photograph of Ft. Wainwright.

Mass interactions between the Chena River and ground-water are monitored by several monitoring wells oriented perpendicular to the river. Continuous water-level stations help illustrate changes in hydraulic head and hydraulic gradient adjacent to the Chena River. Changes in temperature at depth continuously measured by thermistor strings determine the vertical and horizontal extent of bank recharge. These data were used to determine the accuracy of MODFLOW output used for BIOMOC boundary conditions to simulate ground water and surface water mass interactions.

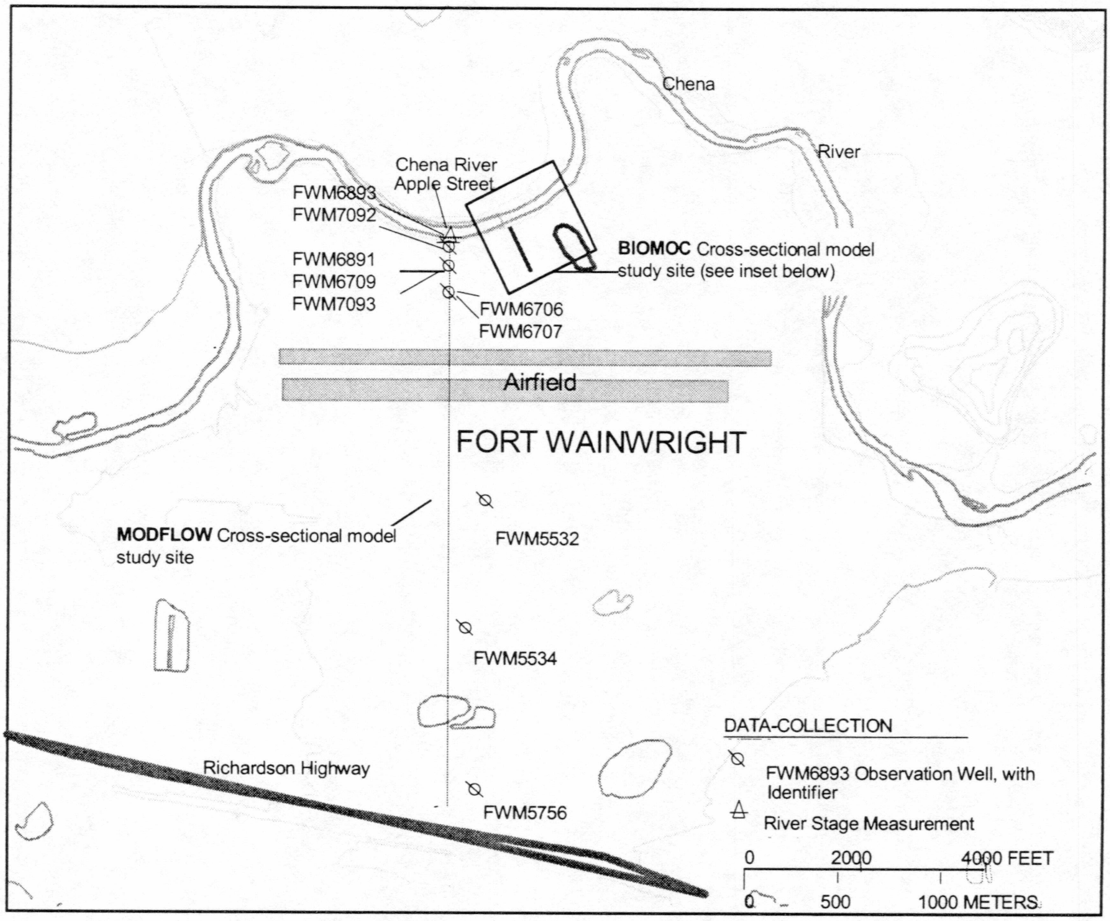
Limited data is available concerning in-situ biodegradation of benzene contamination at Ft. Wainwright. Estimates based on literature values and field measurements were used to define biodegradation parameters. Benzene concentrations measured in the field adjacent to the model domain were used for BIOMOC model input (CH2M Hill, 1999). BIOMOC interprets the effects of transient hydraulic conditions on the transport and anaerobic biodegradation of benzene in the ground water close to the Chena River at Ft. Wainwright, Alaska.

2. MODFLOW AND BIOMOC STUDY SITES

Nakanishi and Lilly's MODFLOW cross-sectional model (1998) represents a slice of the aquifer that is located approximately 1000 ft. downstream to the west of the BIOMOC study site (Figure 3). The two sites are oriented perpendicular to the river to observe the pressure waves caused by instantaneous changes in Chena River stage. The MODFLOW study site uses wells extending 8,800 ft. from the river bank. This allowed Nakanishi and Lilly to model the pressure wave with increasing distance from the river and estimate aquifer properties based on the attenuation of the pressure wave. A detailed description of the MODFLOW study site and model results is provided in the USGS Water-Resources Investigations Report 98-4088.

The BIOMOC study site extends approximately 275 ft. from the river. This smaller section was chosen to observe the ground water and surface water mass interactions. Clusters of sampling wells drilled to different depths give a representation of the portion of the aquifer interacting with the Chena River. As the Chena River stage changes, the sites located along the BIOMOC cross-sectional study site show the amount and extent of bank recharge with changes in ground water chemistry and temperature at depth.

The study site represented by the BIOMOC model is not contaminated with benzene. A benzene plume located 300 ft. southeast of the study site is superimposed onto the cross-sectional model of the study area. Hydrologic and geochemical data collected between 1995 and 1998 are used for establishing initial conditions and testing quality assurance. In order to simulate contaminant recharge from the vadose zone to maintain superimposed field measurements of benzene concentrations, a concentration of 20 μg/l benzene is included with the variable ground water flux at the south end of the BIOMOC cross-section.



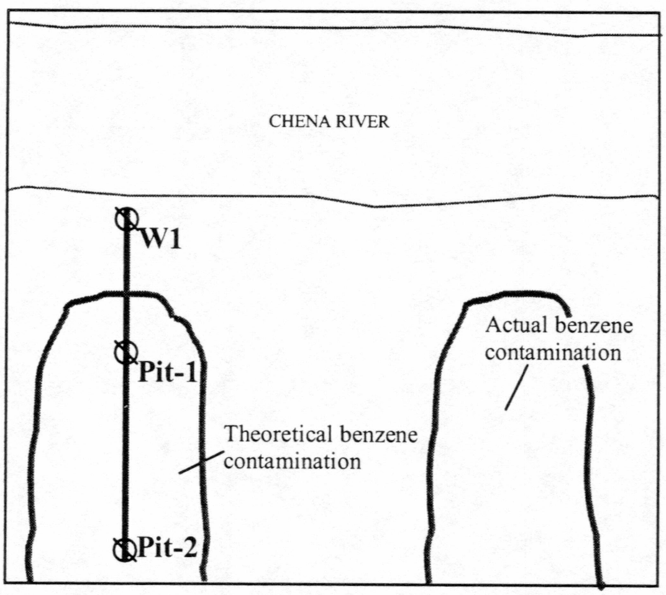


Figure 3. The MODFLOW and BIOMOC model cross-section study sites; hydrologic data-collection sites; actual and theoretical benzene contamination.

3. BACKGROUND

3.1 Geohydrology

Fort Wainwright is located east of Fairbanks in interior Alaska. The Chena River flows throughout Ft. Wainwright and Fairbanks and converges with the Tanana River southwest of Fairbanks. An overview of the hydrology and geohydrology of the Tanana Basin was reported by Anderson (1970) and Nelson (1978). The western and central Tanana Basin is bounded on the north by the Yukon-Tanana Upland, and on the south by the Alaska Range. Ft. Wainwright is located at the southern edge of the uplands. Anderson described various geohydrologic map units for the Tanana Basin, and defined the basin fill near the Tanana River as a floodplain alluvium unit (1970).

The Chena River stage is dominated by winter snow-melt and late summer storms (Glass et al. 1996). In contrast, the Tanana River stage rises primarily during mid-summer, when glacial melt and high elevation snowmelt is at a maximum. Stage changes in the Chena River are typically more transient than those in the Tanana River. The Chena River stage varies 6 to 10 feet with spring snowmelt and summer storms (Glass et al. 1996). During periods of rapidly rising Chena River stage, such as spring snowmelt, ground water flow directions are reversed. Water flows from the Chena River into the ground water system when stage levels are higher than surrounding ground water levels.

Bank recharge during increased river stages can cause mixing of ground water and surface water (Wegner, 1998). Figures 4a and 4b illustrate the conceptual model of a bank recharge event. In spring 1997, spring snow-melt increased the discharge of the

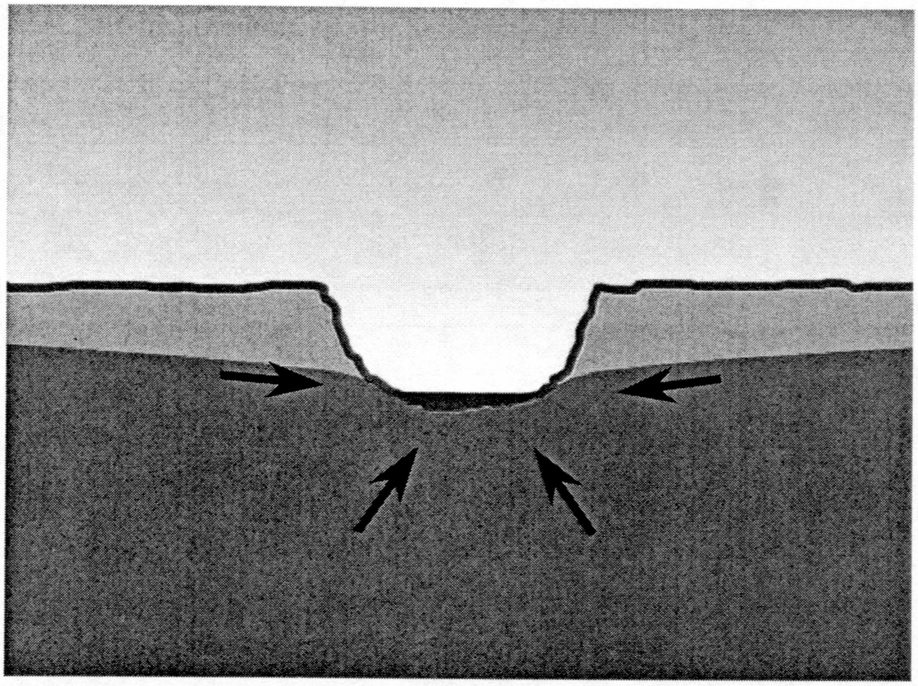


Figure 4a. Conceptual model demonstrating ground water flow into the Chena River at low stage.

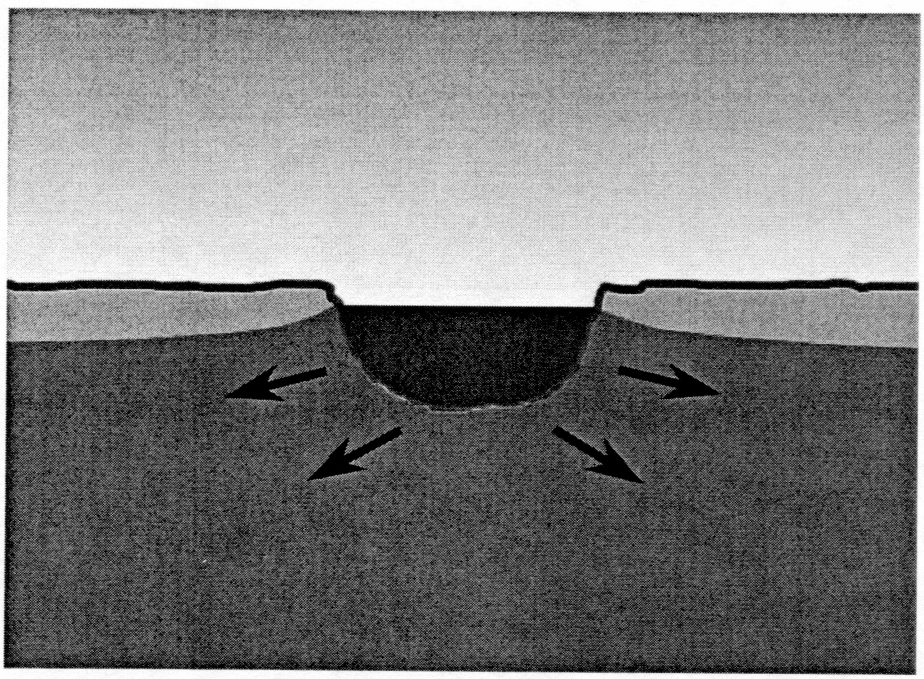


Figure 4b. Conceptual model demonstrating flow gradient reversal, Chena River at high stage

Chena River. The result was a four-foot river stage increase. Hinzman et al. (in review) show variations in temperature, specific conductance, and alkalinity during this event clearly indicate the mass interactions between the Chena River and adjacent water-table aquifer. Bank recharge due to hydraulic gradients and density differences were observed to occur at 20 ft. from the Chena River. Hydraulic gradient, hydraulic conductivity, and bank recharge duration are the greatest contributing factors to the extent of surface water inflow into an aquifer during bank recharge events (Squillace, 1996).

Péwé et al. (1976) described the Chena Alluvium formation in the Fairbanks and Ft. Wainwright areas. The Chena Alluvium is composed of alternating sands and gravel deposited by the Tanana River. The sedimentary facies of the Chena Alluvium is laterally and vertically discontinuous, as is typical of braided rivers (Rust 1978).

The floodplain deposits have been reported to be more than 600 ft (183 m) near Moose Creek Dam by Glass et al. (1996) and approximately 300 ft (~47 m) below the Chena River (Nakanishi and Lilly, 1998). Little is known about the surface of the underlying contact between bedrock and alluvium. Numerous intrusives and hills made up of Fairbanks Schist and other Yukon-Tanana Terrane units project out of the alluvial deposits (Newberry et al. 1996; Péwé 1958; Robinson et al. 1990). These basin structural features indicate that the interface between bedrock and alluvium is discontinuous with respect to elevation. There is potential for bedrock highs that are not exposed above the alluvial land surface. Péwé and Bell described the occurrence of permafrost in the near surface (1975). Lawson et al. have described subsurface permafrost occurrences in selected areas of Ft. Wainwright (1993, 1994). The occurrence of permafrost at depth in the Chena Alluvium, in the Ft. Wainwright area, has not been described in enough detail to define the post-wide distribution of permafrost. The alluvium/bedrock interface used in the BIOMOC model grid was adopted from Nakanishi and Lilly (1998).

3.2 Biodegradation Background

The specific compounds that can be biodegraded and the rates of biodegradation depend strongly on the aquifer reduction-oxidation conditions and microbiological inhibition factors. Field data suggest insufficient oxygen is present in the ground water of the Chena Alluvium aquifer to mineralize contaminants aerobically resulting in predominantly anaerobic conditions (Braddock et al. 1998). During periods of increased river stage, influx of fresh surface water into the ground water system does not affect the concentration of oxygen and, subsequently, the reduction-oxidation conditions (Wegner, 1998). Although BIOMOC is capable of calculating all aerobic and anaerobic biodegradation processes simultaneously, only anaerobic processes are accounted for in the model.

3.3 Governing Equations

Essaid and Bekins (1997) provide a detailed description of the BIOMOC model code. Details of numerical methods implemented for solving the flow and transport equations are fully described by Konikow and Bredehoeft (1978). The following subsections are a summary of the flow, transport, and biodegradation equations of the models presented in this thesis.

3.3.1 Flow Equation

The equation describing transient two-dimensional flow of a homogeneous compressible fluid through a nonhomogeneous anisotropic aquifer is:

$$S\frac{\partial h}{\partial t} = \frac{\partial}{\partial x_j}\left(bK_{jk}\frac{\partial h}{\partial x_k} \right) - W \qquad j,k=1,2$$

Where:

S = storage coefficient (dimensionless)

h = hydraulic head (L)

t = time (T)

K_{jk} = hydraulic conductivity tensor (LT^{-1})

b = aquifer thickness (L)

W = source fluid flux (positive for outflow, negative for inflow) expressed as volume per unit area per unit time (LT^{-1})

x_j = cartesian coordinate (L)

x_k = cartesian coordinate (L)

By Darcy's law, the average linear flow velocity in the x_j direction is given by:

$$V_j = -\frac{K_{jk}}{\varepsilon}\frac{\partial h}{\partial x_j},$$

Where:

ε = effective porosity (dimensionless)

3.3.2 Transport Equation

The two-dimensional transport solved for each solute species is:

$$R_i \frac{\partial C_i}{\partial t} = \frac{1}{b}\frac{\partial}{\partial x_j}\left(bD_{jk}\frac{\partial C_i}{\partial x_k}\right) - V_j \frac{\partial}{\partial x_j} C_i + \frac{W(C_i - C'_i)}{(\varepsilon b)} - R_i \lambda_i C_i - B_i \qquad \text{j,k=1,2}$$

Where:

C_i = concentration of the *i*th solute (ML^{-3})

R_i = retardation factor for the *i*th solute

D_{jk} = dispersion tensor (L^2T^{-1})

C'_i = concentration of the *i*th solute in the source fluid (ML^{-3})

λ_i = first order decay rate constant (T^{-1}) for the *i*th solute (half life $t_{1/2} = (\ln 2)/\lambda$)

B_i = biodegradation reaction term ($ML^{-3}T^{-1}$)

3.3.3 Biodegradation Equation

The total uptake of solute *i* is given by the summation of the uptake for all simultaneously occurring biodegradation processes:

$$B_i = \sum_{n=1}^{N} \beta_i^n v^n \quad ,$$

Where:

N = total number of biodegradation processes

v^n = uptake rate of substrate by biodegradation process *n* ($ML^{-3}T^{-1}$)

$\beta_i^{\ n}$ = uptake coefficient of solute *i* for biodegradation process *n*

3.4 Review of Model Assumptions

The following is a list of assumptions inherent in BIOMOC (Essaid and Bekins, 1997).

1. Flow in only two dimensions is considered.
2. Darcy's law is valid.
3. Porosity and hydraulic conductivity are constant with time, and porosity is uniform in space.
4. Gradients of fluid density, viscosity and temperature do not affect the velocity distribution.
5. Fluid and aquifer properties are not affected by the reactions that occur.
6. Ionic and molecular diffusion are neglected.
7. The aquifer is homogeneous and isotropic with respect to longitudinal and transverse dispersivity.
8. Only the dissolved solute undergoes biodegradation.
9. There is no microbial transport, and the biomass concentration does not drop below the specified initial concentration.
10. A macroscopic approach has been used to represent biodegradation. Biophase diffusion is neglected.

4. LITERATURE REVIEW

4.1 Ground Water and Surface Water Interactions

Ground water and surface water interactions have been measured at Ft. Wainwright since spring 1997. The Chena River stage fluctuations have been uncharacteristically low throughout the course of this study as compared to the previous 30 years of historical data. Hinzman et al. (in review) used changes in temperature, dissolved oxygen, pH, specific conductance and alkalinity at different depths to determine the vertical and horizontal extent of bank recharge during spring melt. The river rose 4.25 ft. (1.28 m) in the span of about three days during 1997 spring melt. As the Chena River rose, the stage level soon overcame the ground water level close to the river and surface water entered the ground water system. The ground water gradient reversal was sustained for a period of one week. Changes in temperature due to the influx of colder surface water were greatest between 14 ft. (4.23 m) and 28 ft. (8.46 m) below the ground surface. Specific conductance and alkalinity results showed that during the spring melt event, river water recharged the aquifer between depths of 17.5 ft and 30 ft (~5.29 m and ~9.1 m, respectively). The majority of influx occurred between 17.5 ft. and 25 ft. (~5.29 m and ~7.55 m, respectively). Alkalinity and specific conductance measurements showed the greatest change at 22.5 ft. (~6.8 m) below the ground surface. The percentage of ground water replaced by surface water was determined with the following equation.

$$GW_{displaced}(\%) = \frac{(P_0 - P_1)}{(P_0 - P_r)}$$

Where:

$GW_{displaced}$ = Percent of groundwater displaced by surface water

P_0 = Parameter measured prior to event

P_1 = Parameter measured at its greatest change

P_r = Parameter measured at river

Wegner (1998) estimated that 64 to 68 percent of ground water at the measuring point 20 ft. (6.1 m) from the river was replaced by surface water during the bank recharge event. Alkalinity and specific conductance measurements were made two days after the highest stage recorded during the snow-melt event. These field measurements may underestimate the percentage of mixing during the snow-melt event.

Squillace et al. (1996) studied the Cedar River in Iowa to determine the infiltration of surface water into the adjacent aquifer during high-stage events. Surface water displaced ground water to an extent of 100 ft. (~30.21 m) and a depth of 20 ft. (~6.04 m) during peak river stage events. Seventy percent of the water moved through the riverbed and thirty percent through the riverbanks. Numerical simulations showed influx of surface water to an extent of 100 ft. (30.21 m) and a depth of 13 ft. (3.93 m). The high river stages resulting in ground water gradient reversal lasted two weeks. The maximum stage changes on the Chena River are higher than those on the Cedar River. The hydraulic conductivity of the Chena Alluvium is at least three times greater. However, the storm peaks and snow-melt events have shorter duration. Given the differences between the Chena Alluvium and the Cedar River Aquifer, it is expected that the Chena River water would infiltrate into the adjacent aquifer greater than 100 ft.

(30.21 m) from the river. Numerical simulations that include typical river stages and atypical river stages of the Chena River are necessary to fully understand ground water and surface water mass interactions.

Nakanishi and Lilly (1998) used MODFLOW to simulate ground water and surface water interactions in order to estimate aquifer properties. The model represents a cross-sectional slice of Chena Alluvium extending perpendicular to the Chena River 9,000 ft. (~2682 m). The model was calibrated by matching observed water levels to simulated water levels during peak flows of the Chena River. Changes in river stage were attenuated with distance from the river. At 1000 ft. (305 m) from the river, the rise in the water table was approximately 40 percent of the rise in river stage, and approximately 10 percent at 9000 ft. (2.7 km). Table 1 lists the estimated aquifer properties.

The model simulates horizontal and vertical flow directions near the river during periods of varying river stage. This cross-sectional MODFLOW model is used to define boundary conditions in BIOMOC simulations in this study.

Table 1. Estimated values of geohydrologic properties for Chena Alluvium and bedrock near Fairbanks, Alaska (Nakanishi and Lilly, 1998).

Parameter	Estimated value corrected for river geometry effects (English units)	Estimated value corrected for river geometry effects (SI units)
Riverbed conductance	350 ft^2/d	33 m^2/d
Chena Alluvium		
Vertical hydraulic conductivity (**K_v**)	20 ft/d	6 m/d
Horizontal hydraulic conductivity (**K_h**)	400 ft/d	122 m/d
Anisotropy (**K_v /K_h**)	1:20	1:20
	Assumed value (English units)	Assumed value corrected for river geometry effects (SI units)
Specific Yield (**S_y**)	0.25	0.25
Specific Storage (**S_s**)	$1x10^{-6}$	$1x10^{-6}$
Diffusivity (**K_h /S_y**)	1,600 ft/d	488 m/d
Bedrock Units		
Vertical hydraulic conductivity (**K_v**)	0.005 ft/d	0.002 m/d
Horizontal hydraulic conductivity (**K_h**)	0.10 ft/d	0.03 m/d
Specific Storage (**S_s**)	$1x10^{-6}$	$1x10^{-6}$

4.2 Benzene Transport and Biodegradation

Lilly and others (1996) offer a discussion on solute transport in the Railroad Industrial Area, Fairbanks, Alaska. Advection, dispersion, and molecular diffusion combine effects to transport contaminants and increase the spatial dimensions of plumes. Advection is the macro-scale transport of dissolved constituents by the motion of flowing ground water. Longitudinal dispersion is the spreading of solutes in the principal direction of flow due to differences in the velocity flow field. Transverse dispersion is the spreading of solutes perpendicular to the direction of flow due to differences in the velocity flow field. The reduction of solute transport is also affected by sorption processes. Organic compounds have a low affinity for water and adsorb onto the mineral surfaces of aquifer material or partition into naturally occurring organic matter. All of these factors are accounted for in the BIOMOC model simulations. Transverse and longitudinal dispersion are assumed by BIOMOC to be isotropic. The linear sorption distribution coefficient for benzene is estimated to be 0.093 $ft^3/\mu g$ (Essaid and Bekins, 1998).

Benzene is the most recalcitrant of the aromatic hydrocarbons to biodegrade and the most soluble. For this reason, the in-situ biodegradation of benzene in the Ft. Wainwright area is important to study. In 1994, Harding Lawson Associates analyzed ground water samples from the East Quartermasters Area for chlorinated hydrocarbons and BTEX (benzene, toluene, ethylbenzene, and xylenes) in 27 small-diameter wells (Harding Lawson Assoc., 1995). From 1995 to 1998, USGS and UAF-WERC measured benzene concentrations in the same area where an underground fuel storage tank had been contaminating the ground water for at least 20 years (McCarthy et al. 1998). Concentrations of benzene ranged from 27 μg/l to 0 μg/l in the saturated zone (CH2M Hill, 1999). Contaminant concentrations measured adjacent to the study site are listed in table 2.

Natural attenuation of chlorinated hydrocarbons has been observed 500 ft. (~150 m) up river of the study site (McCarthy et al., 1998) and benzene concentrations in the area appear to be stable. The presence of other contaminants, such as toluene, ethylbenzene, and xylenes, in the area are most likely inhibiting the natural attenuation of the minor benzene concentrations (White, personal comm., 2000). The rate of benzene biodegradation in the vadose zone (smear zone) is unknown. Also, the input rate of benzene from the smear zone into ground water is unknown. Estimates based on benzene concentrations measured in ground water adjacent to the model domain are used to define a theoretical contaminant source at the water table interface in the BIOMOC model. The BIOMOC model is unable to simulate a smear zone or any reactions in the vadose zone.

CH2M Hill (1997) has done extensive ground water and solute transport modeling in the OU5. The primary objective of their modeling efforts is to support decision-making at remedial sites. MODFLOW was used to construct an areal ground water flow model for the Building 1060 area in OU5 on Ft. Wainwright. Model calibration compared simulated water levels with those measured in the field. Transient changes in Chena River stage were incorporated in the model by calibrating the model to water levels measured from June 20 to July 20, 1995. Historic Chena River data was used to produce monthly average river stage levels. Monthly time steps were used to predict 25 years of ground water flow. Monthly average stage elevations of the Chena River are lower than instantaneous peak values. Monthly averages are also imposed in the model for a longer period of time (30 days) than peak fluctuations last (4 to 5 days) (CH2M Hill, 1997).

CH2M Hill evaluated several remedial options for benzene contaminated aquifer material using solute transport code MT3D[96]. One remedial option evaluated was the natural attenuation of benzene in the building 1060 area. Natural attenuation in this case is chemical degradation, which is the half-life for benzene assumed to be 1.9 years.

Table 2. Contaminant concentrations measured near the study site (CH2M Hill, 1999).

Well I.D.	Date	DRO (ppb)	GRO (ppb)	B (ppb)	E (ppb)	T (ppb)	X (ppb)
FWM7485	Dec-97	310	ND	ND	ND	ND	ND
FWM7485	Apr-99	ND	ND	ND	ND	ND	ND
FWM7486	Dec-97	300	ND	6.9	ND	ND	ND
FWM7486	Apr-99	280	ND	8.0	ND	ND	ND
FWM7487	Dec-97	530	93	6.0	ND	ND	ND
FWM7487	Apr-99	500	160	15	ND	ND	ND
FWM7488	Dec-97	430	20	0.43	ND	ND	ND
FWM7488	Apr-99	ND	ND	ND	ND	ND	ND
FWM7489	Dec-97	590	200	21	ND	ND	ND
FWM7489	Apr-99	620	180	8.0	ND	ND	ND
FWM7490	Dec-97	550	130	1.7	ND	ND	ND
FWM7490	Apr-99	600	250	13	ND	ND	ND
FWM7491	Dec-97	360	90	6.5	ND	0.73	0.5
FWM7491	Sep-98	ND	ND	ND	ND	ND	ND
FWM7491	Apr-99	390	170	9.0	ND	ND	ND
FWM7492	Dec-97	NA	25	ND	ND	ND	ND
FWM7492	Apr-99	ND	ND	ND	ND	ND	ND
FWM7493	Dec-97	320	120	1.7	1.6	8.9	7.9
FWM7493	Apr-99	280	ND	ND	ND	ND	ND
FWM6894	Sep-94	340.0	430.0	27.0	ND	ND	ND
FWM6894	Sep-95	173.0	175.0	18.0	0.4	0.6	0.13
FWM6894	Sep-98	320.0	130.0	11.0	0.1	0.2	ND
FWM6894	Apr-99	360.0	290.0	25.0	ND	2.0	ND
FWM7072	Sep-95	46.0	31.0	ND	ND	ND	ND
FWM7072	Apr-99	ND	ND	1.0	ND	ND	ND
FWM7073	Sep-95	109	284	1.2	0.2	ND	1.0

DRO, Diesel-Range Organics
GRO, Gasoline-Range Organics
B, Benzene
E, Ethylbenzene
T, Toluene
X, Xylene

Actual half-life values that will occur at the site depend on the availability of electron acceptors. After approximately eight years of transport, the simulated mass flux of benzene stabilizes at about 0.4 gal/day. CH2M Hill reported that 80 percent of benzene in the aquifer is chemically degraded before it enters the Chena River (1997).

A study of the anaerobic biodegradation of benzene, toluene, ethylbenzene, and xylene isomers in aquifer material was conducted by Borden et al. (1997) in Michigan and North Carolina. It was found that benzene, toluene, ethylbenzene, and the xylene isomers (BTEX) are anaerobically biodegradable under ambient subsurface conditions using ferric iron, sulfate and/or carbon dioxide as terminal electron acceptors. The observed order of biodegradation varied between the two sites studied with toluene being the most rapidly biodegraded compound. The more easily biodegraded compounds (toluene, o-xylene, m-xylene) appeared to biodegrade to low but detectable (10 – 30 μg/l) concentrations after which biodegradation slowed or stopped. It is unknown if biodegradation of these compounds will continue once the more recalcitrant compounds are depleted. Borden et al. (1997) found that in order to accurately simulate the anaerobic biodegradation of individual BTEX compounds, a model that includes two variables will be required: (1) the lag period prior to biodegradation, and (2) the rate of biodegradation. The contamination in the OU5 area on Ft. Wainwright has been residing in the aquifer material for at least 20 years, thus a lag period has already occurred. The rate benzene biodegrades at OU5 on Ft. Wainwright is unknown. Borden et al. (1997) calculated in-situ decay rates for BTEX compounds averaged over the entire plume at Rocky Point, North Carolina and found benzene to decay at a rate of 0.0002 d^{-1}. It is assumed in the BIOMOC model simulations that anaerobic microbes in the ground water will use ferric iron, sulfate, and/or nitrate as terminal electron acceptors to biodegrade benzene at a rate of 0.0002 d^{-1}. A yield of 0.2 and a half-saturation constant of 1 mg/l are assumed in the BIOMOC model. These values were used in the BIOMOC model to define anaerobic biodegradation of benzene in the alluvial aquifer material. Table 3 lists the BIOMOC input parameters.

Braddock and others (1998) assessed the potential for biodegradation of petroleum hydrocarbons in the Railroad Industrial Area, Fairbanks, Alaska. This area is approximately 1.5 miles (2.5 km) downstream from Ft. Wainwright. The study was designed to document that microorganisms from the Railroad Industrial site have the potential to transform contaminants under site conditions. Temperature, nutrient availability, and the concentration of dissolved oxygen, nitrate, sulfate, and Fe(III) were found to control the rate and extent of natural attenuation in contaminated ground water. The average temperature of water in wells from the Railroad Industrial Area averages between 4 and 5 °C which is similar to conditions on Ft. Wainwright. When the total activity of the heterotrophic microbial population was examined after two-day incubations in the laboratory at 4, 10, 15, and 22 °C, they found no activity at 4 or 10 °C and a large increase of activity between 15 and 22 °C. After a 10-day incubation period, microorganisms from contaminated wells were able to completely break down benzene at 10 °C. Although biodegradation at the site might be increased by nutrient additions, naturally occurring nutrients were adequate for microbial breakdown of petroleum hydrocarbons in the laboratory. In-situ biodegradation rates of benzene were not reported, however, preliminary evidence that chemical species other than oxygen, such as sulfate, may contribute to microbial degradation of petroleum contaminants at the Railroad Industrial Area. Microbial populations measured in ground water reported by Braddock and others (1998) are similar to those used for BIOMOC biomass parameters. An initial population of 4300 cells/ml of benzene degraders is assumed in the BIOMOC model simulations.

Table 3. Hydrologic and biodegradation parameters used for BIOMOC input.

Hydrologic parameter	Literature values	References
Horizontal hydraulic conductivity (K_H)	400 ft./day	Nakanishi and Lilly
Vertical hydraulic conductivity (K_V)	20 ft./day	Nakanishi and Lilly
Porosity	0.40	Nakanishi and Lilly
Storage coefficient	1.0×10^{-6}	Nakanishi and Lilly
Horizontal dispersivity	6.6 ft.	Nakanishi and Lilly
Anisotropy (K_V/K_H)	1/20	Nakanishi and Lilly
Biodegradation parameter	Literature values	
Initial maximum concentration of benzene in ground water	27 μ g/l	CH2M Hill
Initial maximum concentration of benzene in Chena River water	0 μg/l	CH2M Hill
Number of biodegradation processes	1	Borden et al.
Asymptotic maximum specific uptake rate (V_{max})	0.0002 d^{-1}	Borden et al.
	Assumed values	
Yield (Y)	0.2	White, Braddock
Benzene half saturation constant (K_b)	1,000 μ g/l	White
Anaerobic degrader biomass	4300 cells/ml	White, Braddock
Aerobic degrader biomass	0 cells/ml	--

5.0 METHODS

5.1 Site Description

The study area is located south of the Chena River on Ft. Wainwright (Figure 5). Wegner (1998) documented the construction of each data-collection site in detail. In 1997, a line of monitoring wells were installed extending approximately 300 ft. (90.63 m) perpendicular to the river. The line of wells is consistent with a cross section of the alluvium parallel to the direction of ground water flow. The bank of the Chena River is not vertical. A measuring point at the edge of the river during low stage was used to determine horizontal distances. The surface of the river is approximately 15 ft. (4.53 m) below the ground surface elevation at the study site at low stage.

The site selection for the three continuous data collection sites was such that the transient hydraulic conditions caused by the rapid rise and fall of the Chena River stage could be observed. The installation of the sites perpendicular to the river allows for a cross-sectional analysis of the surface water and ground water interactions.

The sites are also adjacent to an area of known benzene contamination originating from the southeast side of building 1070. From 1995 to 1998, USGS and UAF-WERC measured benzene concentrations in wells located adjacent to building 1070 (Figure 5). Although the three continuous data collection sites are not within the contaminated area, their locations are ideal for understanding the change in geochemical parameters during transient hydraulic conditions governing the adjacent area that is contaminated.

The following subsections summarize the construction of each data-collection site. A detailed description of site-construction is provided by Wegner (1998).

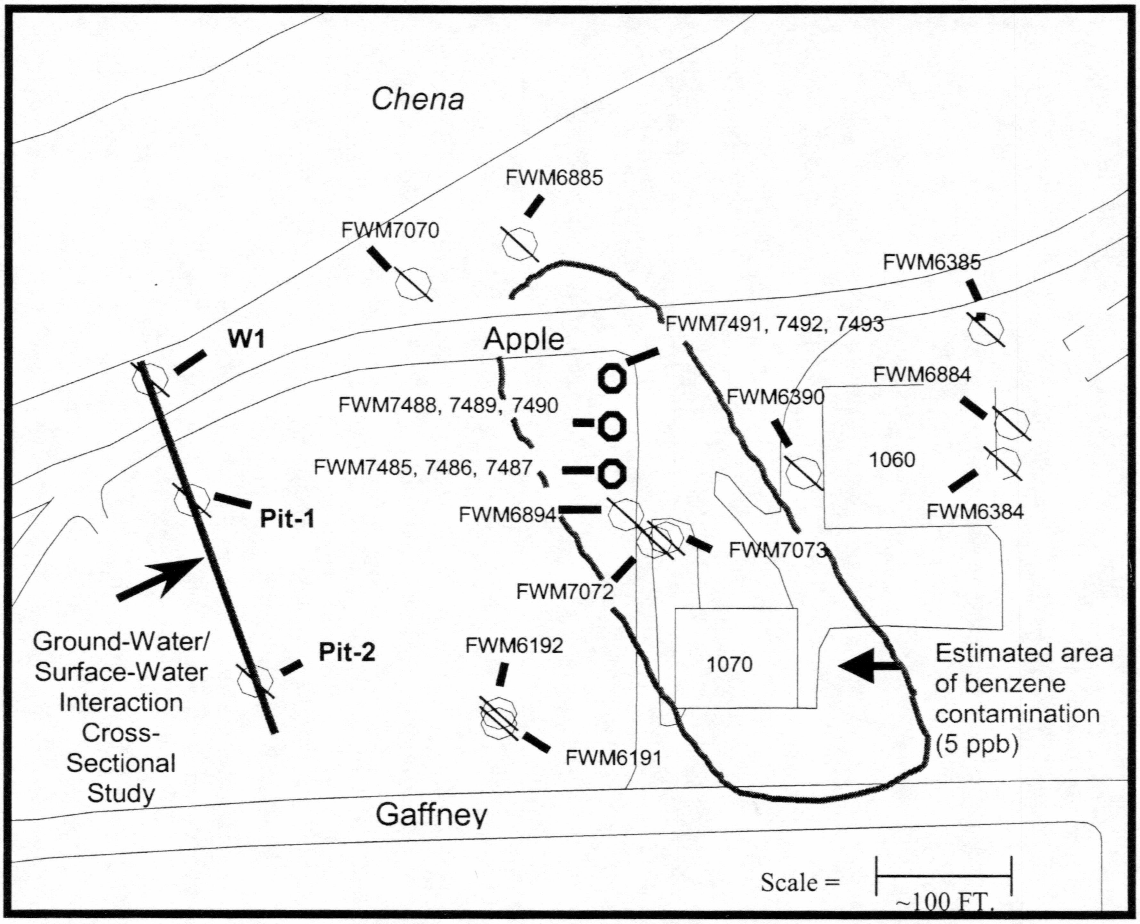


Figure 5. Project site (after CH2M Hill, 1999).

5.1.1 Site W1

A 6-inch hollow stem auger with an inner diameter of 4-inches was used to bore three holes to a depth of 40 ft., 20 ft. from the bank of the Chena River. Two-inch screens (10 slots/in.) were cut with a hacksaw across several one-inch PVC pipes. Clusters of two to three monitoring wells were installed at different depths for a complete representation of the aquifer. The commercial well screen for the 2-inch PVC pipe water table well is 12.5 feet in length. A pressure transducer was installed inside the water table well and then connected to a Campbell Scientific CR-10 data logger located at the site. A string of 25 thermistors was affixed to a 1-inch PVC pipe and lowered down a bore-hole. The thermistors were placed in sequence along the PVC pipe from 10 to 30 feet below the ground surface. The thermistor string was then connected to a Campbell Scientific CR-10 data-logger. Six feet of metal casing was installed over each boring with 3 ft. remaining above ground. Metal instrument cases were welded on top of the casings to provide security for the wells and the instrumentation. To ensure the wells were nested in unconsolidated fill, the auger was counter-rotated while being slowly removed from each boring (Wegner, 1998).

5.1.2 Site Pit-1

A series of wells were installed in a 23 (~7.01 m) ft. deep pit excavation, 100 ft. from the Chena River, in October 1996. A water table well, constructed of 2-inch PVC pipe with a 12.5 ft. screen, was drilled to a depth of 22.5 ft (~6.86 m). A pressure transducer affixed to the water table well was wired to a data-logger located at the site. Several monitoring wells constructed of 1-inch PVC pipe, each with 2-inch well screens at different depths, were installed for a complete representation of the aquifer. A string of 25 thermistors was affixed to a 1-inch PCV pipe between 0 and 18 feet and placed into the pit. The thermistors were then connected to a data-logger. Eighteen time domain reflectometry (TDR) probes were placed in the north wall of the pit to measure soil moisture content at different depths. A second CR-10 is used for the collection of the

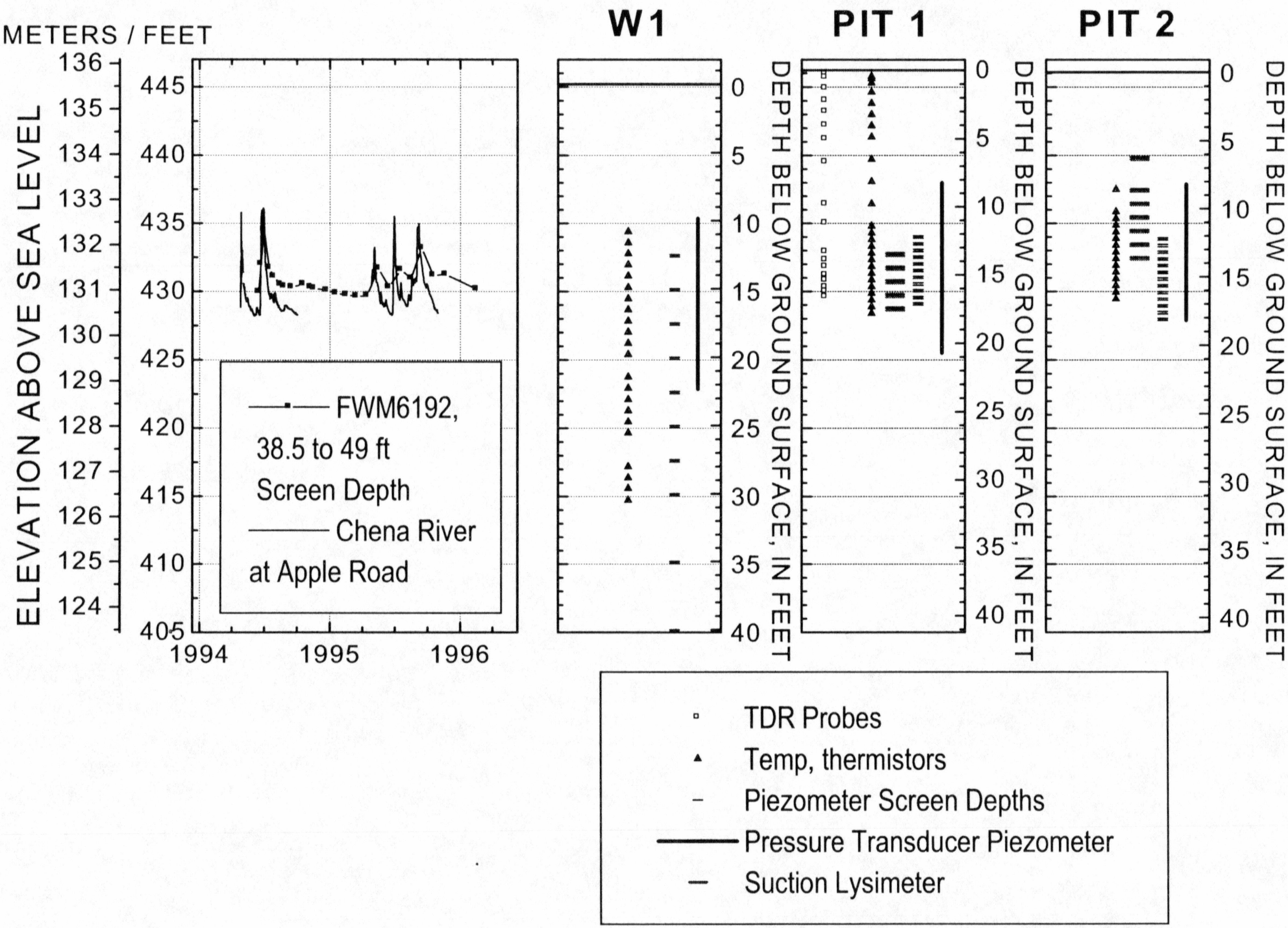
TDR data. The excavation was carefully back-filled by an excavator. A TDR unit used to calculate the soil moisture content was placed in an instrumentation shelter at the surface. Instrumentation shelters containing the data-loggers and well casing shelters were installed around the monitoring wells (Wegner, 1998).

5.1.3 Site Pit-2

A second excavation identical to the Pit-1 pit was created 275 feet from the river bank and denoted as Pit-2. A water table well constructed out of 2-inch PVC pipe with a 12.5 ft. screen was placed into the excavated pit. A pressure transducer affixed to the water table well was wired to a Campbell Scientific CR-10 data-logger located at the site. Several monitoring wells constructed of 1-inch PVC pipe, each with 2-inch well screens at different depths, were installed for a complete representation of the aquifer. A string of 15 thermistors was affixed to a 1-inch PCV pipe between 7 and 18 feet and placed into the pit. The thermistors were then connected a CR-10 data-logger. The excavation was carefully back-filled with an excavator. An instrumentation shelter containing the data-logger and well casing shelters were installed around the monitoring wells (Wegner, 1998).

The orientation and location of the study area is ideal for analyzing ground water and surface water mass interactions. Data collected from the study site was used to test the validity of transport calculations performed by the BIOMOC model.

Figure 6. Depths of thermistors, TDR probes, lysimeters, and water table wells at W1, Pit 1 and Pit 2 (After Wegner,1998).



5.2 Conceptual Model

Ground water and surface water flow are treated as two-dimensional. The Chena River is a sink and source at the northern end of the cross-section. When the Chena River stage rises, bank recharge occurs, and bank discharge occurs as stage declines. The Chena River is treated as a ground water divide which assumes that no ground water flows under the Chena River. The aquifer system is the source of water on the southern end of the cross section. The alluvial aquifer is assumed to be a homogeneous and anisotropic system. The alluvium/bedrock interface is assumed to be a no-flow boundary at a depth of 99.3 ft. (30 m) and is the vertical extent of the model. Recharge and evapotranspiration are assumed to be negligible (Nakanishi and Lilly, 1998).

5.3 Numerical-Model Construction

The BIOMOC model grid was constructed to be compatible with Nakanishi and Lilly's (1998) MODFLOW model grid. The grid represents a cross-sectional slice of the aquifer 99.3 ft. (~30 m) thick, 390.58 ft. (~118 m) long, and unit width of 1 ft. (~0.305 m). The boundary conditions and hydrogeological parameters of the numerical grid were defined by Nakanishi and Lilly's MODFLOW simulation of ground water and surface water interactions and steady-state initial conditions.

The study sites Nakanishi and Lilly used for calibrating MODFLOW simulations are located approximately 1000 ft. down stream of the sites used in this study. Water levels and hydraulic gradients are comparable for each site.

Nakanishi and Lilly's numerical model grid contains 45 columns, 1 row, and 11 layers for a total of 495 cells (Figure 7). The total length and thickness of the grid is 9,000 ft. (2719 m) and 1,032 ft (~312 m), respectively. This cross-sectional slice of the aquifer is one foot wide. The BIOMOC model grid represents 10 columns, 1 row, and 6 layers of The cross-sectional MODFLOW model grid, which includes a profile of the Chena River at the north boundary and three monitoring wells extending from the simulated riverbank. The BIOMOC cross-sectional slice is 1 ft (0.305 m) wide. This grid was chosen to match study site conditions and describe the details of surface water interactions with benzene contaminated ground water.

Nakanishi and Lilly defined the boundaries of the MODFLOW model grid with time-variant specified head cells at the north and south boundaries. Water levels measured in the field were used to calibrate the model. They used a systematic progression of testing boundary conditions for the model, initial head conditions, time discretization, and aquifer properties. The primary area of calibration was the northern 1,000 ft. of the model. This calibrated MODFLOW model defines the boundary conditions for BIOMOC in this study.

Chena River stages collected during the summers of 1995 through 1998 and water levels at FWM5756 collected during the summer of 1995 were used in a regression analysis to determine the water levels in well FWM5756 for 1996 through 1998 (Figure 8). The regression analysis is in the Appendix. These data sets were used to designate water levels at the time-variant specified head boundaries of the MODFLOW model. Chena River data used in the MODFLOW model did not include winter recession.

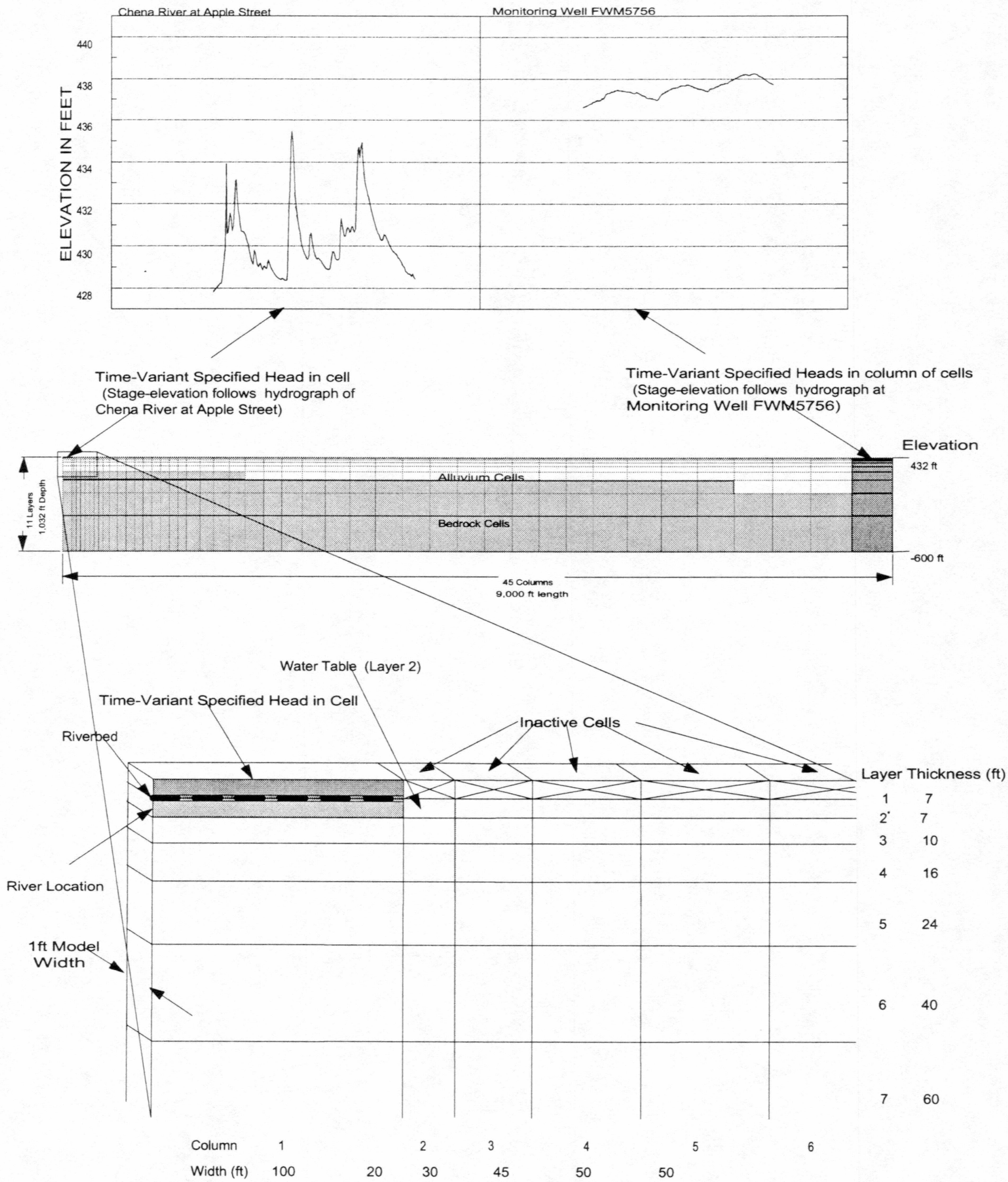


Figure 7. The cross-sectional MODFLOW numerical model grid, Ft. Wainwright, Alaska (After Nakanishi and Lilly, 1998).

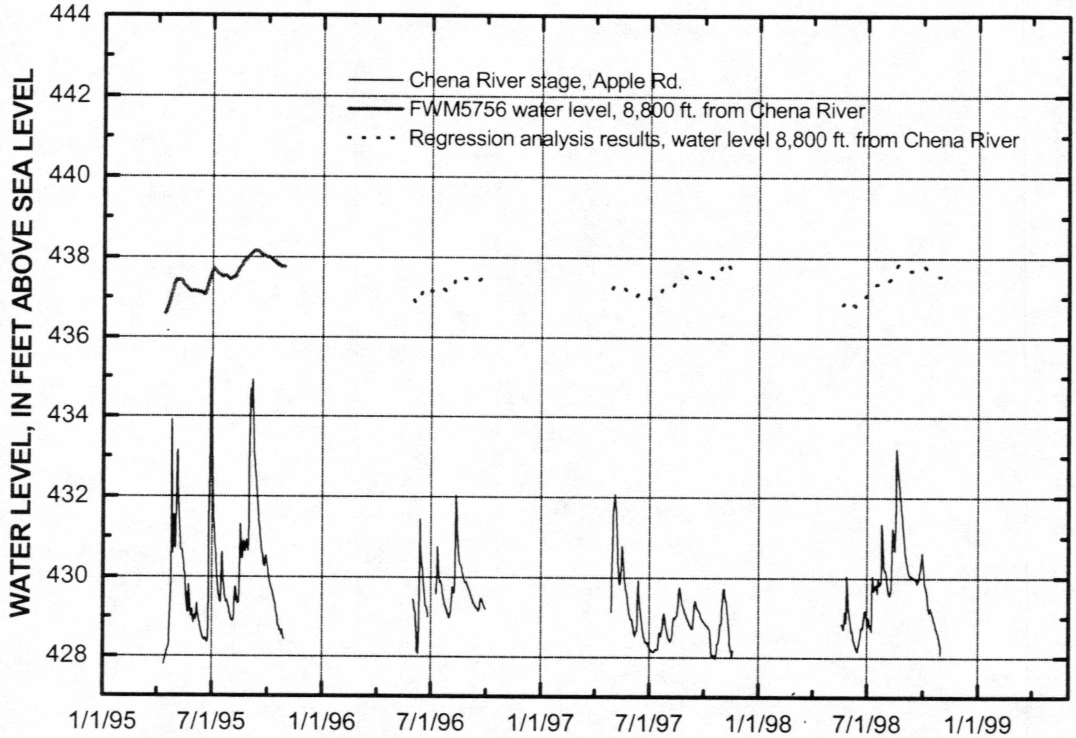


Figure 8. Chena River stage data and monitoring well FWM5756 water levels used to define time-variant specified head boundaries in The cross-sectional MODFLOW model (1998).

BIOMOC allows two types of boundary conditions: constant head or prescribed flux. Prescribed flux boundaries were used in this study to simulate transient hydraulic conditions. Pumping/injection wells were placed at the appropriate nodes of the model grid to define prescribed flux boundaries in BIOMOC. Initial conditions giving the starting heads of the transient simulations were determined by a steady-state model run of the latter half of winter recession when large changes in ground water flow rate and direction do not occur.

BIOMOC requires the model grid be surrounded by a no-flow boundary, resulting in the first and last cell of every column and layer to be a no-flow cell (Figure 8). Columns 2 through 15 and layers 2 through 4 of the BIOMOC model grid represent half of the profile of the Chena River. The riverbed was defined by a series of 14 pumping/injection wells in layer 4 at the north end of the model. These cells represent the MODFLOW cell in column 1, row 1, layer 3. The riverbank is defined by two pumping/injection wells in column 15, row 1, layers 2 and 3. These cells represent the MODFLOW cell in column 2, row 1, layer 2. The regional ground water flow from the south end of the model is defined by a series of 28 pumping/injection wells in column 117, layers 2 through 29. These cells represent MODFLOW column 10, row 1, layers 2 through 6 (Figures 7 and 9).

Cell-by-cell fluxes calculated by MODFLOW for each stress period were used to define prescribed flux boundaries, or pumping and injection rates at appropriate nodes, of the BIOMOC model grid. Ground water and surface water fluxes of the cells defining the Chena River in the MODFLOW model grid were used to define the northern boundary of the BIOMOC model grid. Ground water fluxes calculated in column 10 of the MODFLOW model were used to define the southern boundary of the BIOMOC model. Time-variant flow was computed by defining a series of pumping periods in the BIOMOC input file. Each pumping period is equivalent to a MODFLOW stress period. Fluxes from appropriate cell faces in the MODFLOW grid for each stress period were reported and used to prescribe the flux at each boundary of the BIOMOC model. Winter recession is approximated by repeating the last pumping period of each summer until the

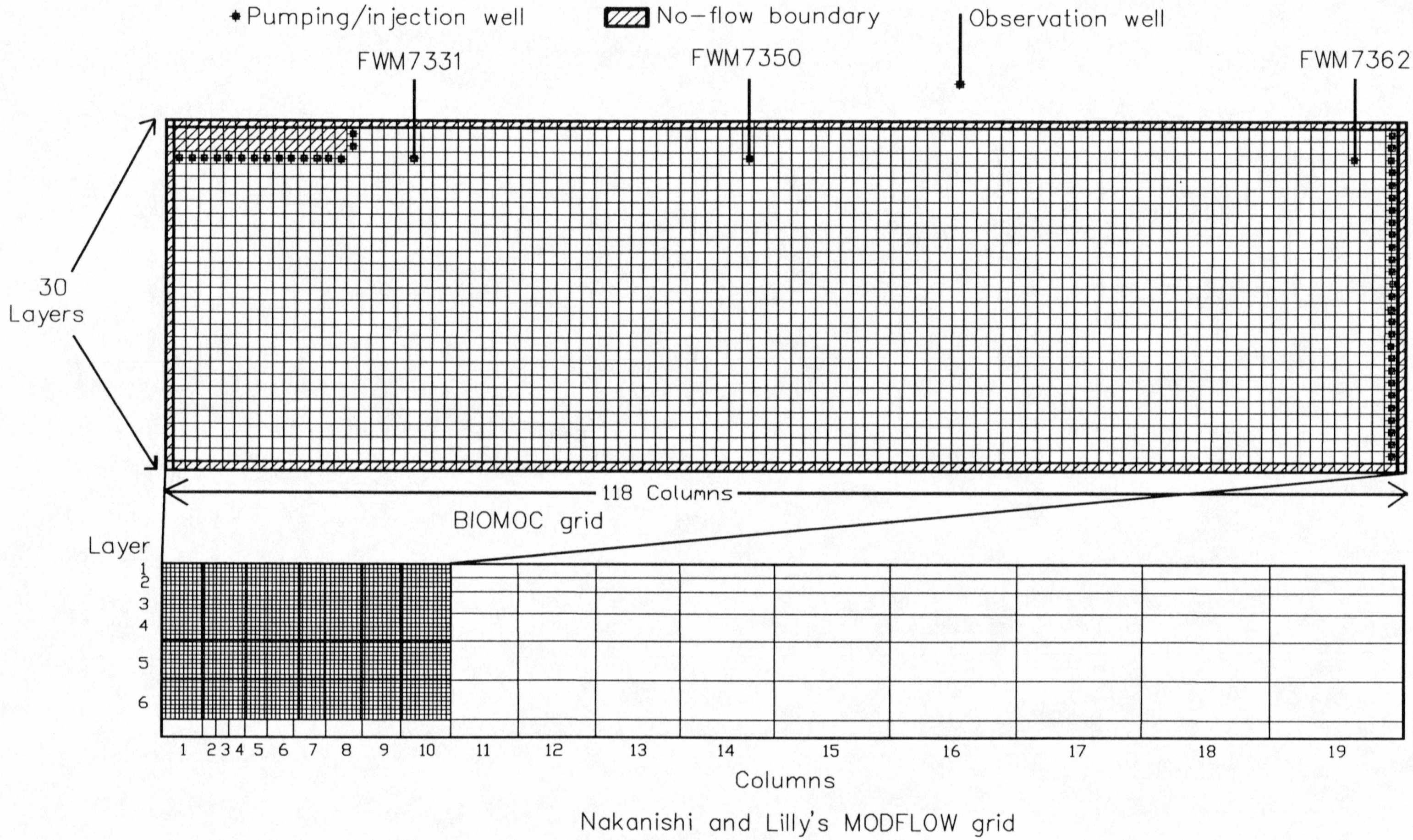


Figure 9. BIOMOC numerical model grid overlaying MODFLOW model grid.

beginning of the next data set. A total of 682 pumping periods represent hydrologic years 1995 through 1998 in the BIOMOC model.

The MODFLOW model assumes the Chena River is a ground water divide. This means no ground water flows under the Chena River in the simulations. The error introduced by this assumption is not significant for the purpose of analyzing aquifer properties, however, the error is significant when studying solute transport. The errors are caused by two-dimensional effects in a three-dimensional flow regime and the use of specified head boundaries to constrain the MODFLOW model. By specifying heads at either boundary, only the water levels are controlled, not the volume of water entering and leaving the system at particular cells. Assuming there is no ground water flow beneath the Chena River requires the entire water budget to discharge into the river, through the riverbed and the riverbank. This results in relatively high flux rates into and out of the river. This introduces considerable error in ground water velocities near the river when prescribed flux boundaries are used. The amount of draw-down caused by pumping rates of wells defining the Chena River results in dramatic increases of hydraulic gradients close to the river. This increases the ground water velocity considerably adjacent to the river. The effect on the southern boundary is not as dramatic but apparent. However, at a distance from each boundary, ground water velocities approach realistic values. Ground water velocities range from 210 ft/day to 6.10 ft/day in the BIOMOC model.

Figures 10 and 11 show the horizontal ground water velocity profile for the first fifteen days of the simulation in layers 2 through 5. During this period, the first bank

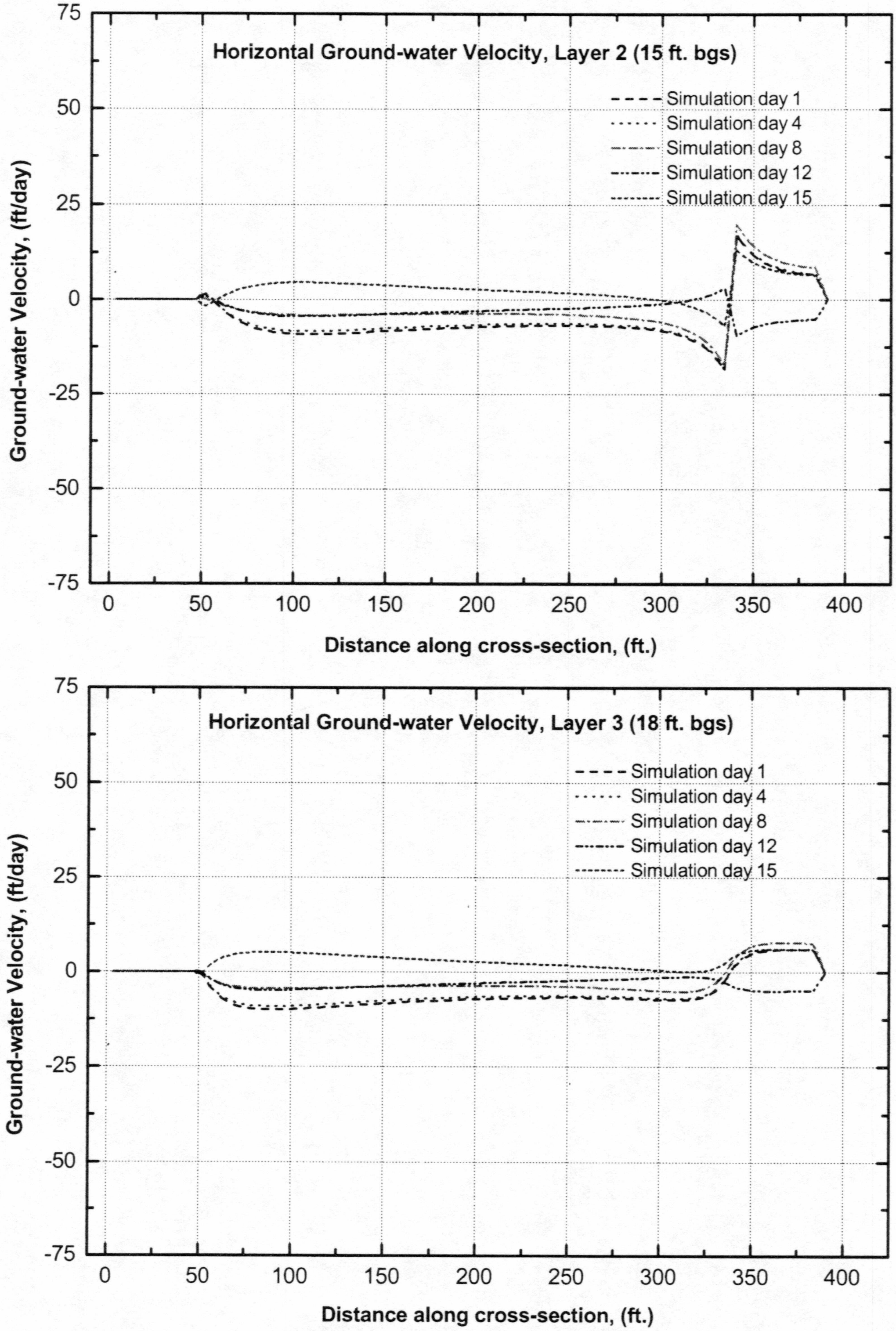


Figure 10. Horizontal ground water velocity profiles of BIOMOC layers 2 and 3.

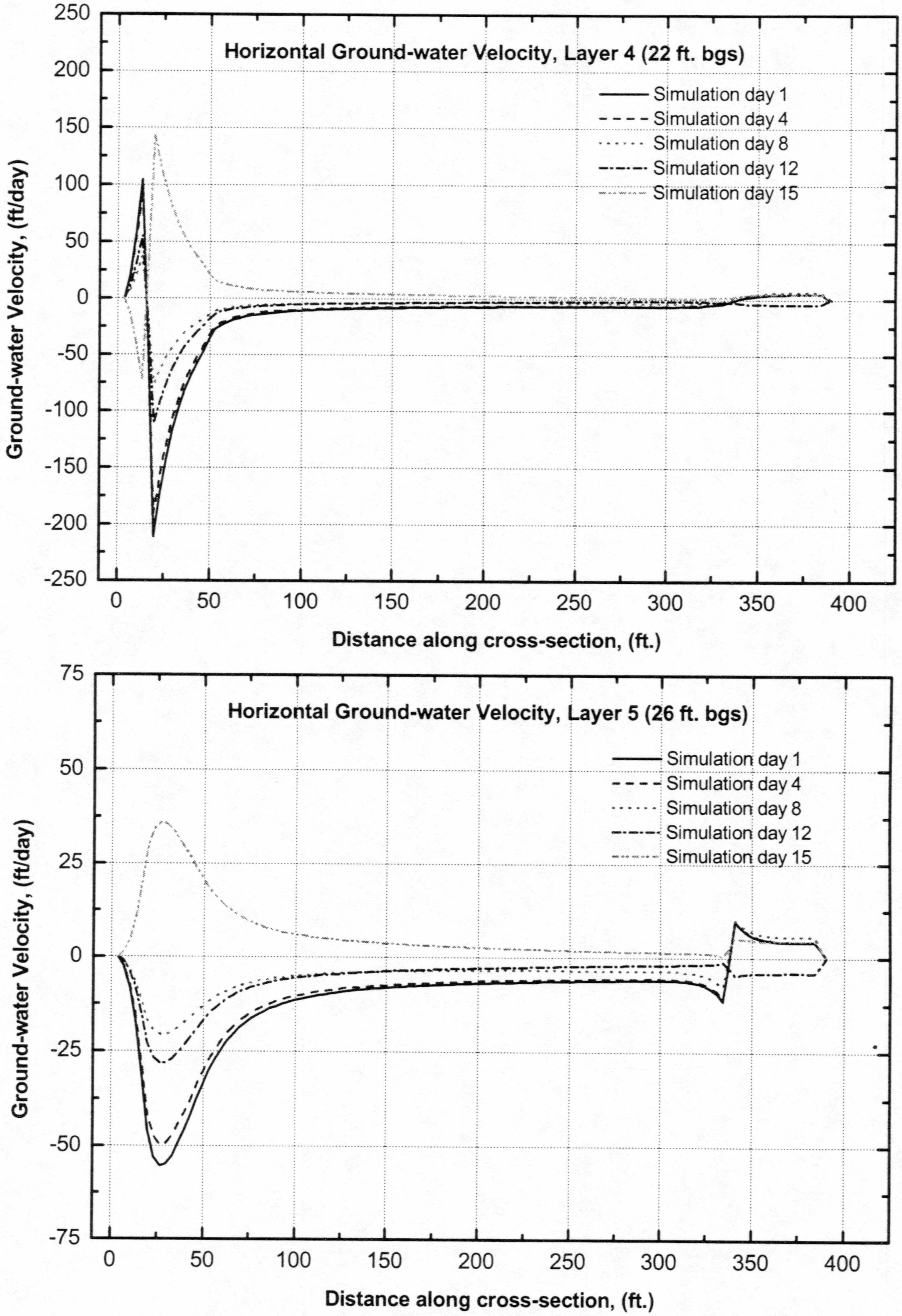


Figure 11. Horizontal ground water velocity profiles of BIOMOC layers 4 and 5 (Please note differences in y-axis scales).

recharge event of 1995 causes the changes in ground water velocity. Ground water moving toward the river and discharging has a negative velocity, ground water moving away from the river has a positive velocity. During the first fifteen days of the simulation (4/12/95 through 4/27/95), the ground water gradient reverses, resulting in bank recharge. The plots show the erroneous ground water velocities near the river, and especially beneath the river in layers 4 and 5 of the BIOMOC model (Figure 11). The sharp velocity change near the boundaries of the model, generally seen on the plot as a near vertical line crossing the zero axis, is due to the presence of the no-flow boundary directly adjacent to pumping/injection wells defining the prescribed flux nodes of the model grid.

The area being studied to determine simulated changes in geochemistry and microbiological activity is directly adjacent to the model boundaries where the greatest instability occurs. The stability of BIOMOC calculations is directly related to ground water and surface water fluxes. It is understood that a certain amount of ground water discharges into the Chena while the majority flows beneath the Chena River to the west with the regional ground water flow. The volume or percentage of the water budget that flows beneath the Chena River is unknown. The use of Nakanishi and Lilly's MODFLOW model to define the flow system is the best approximation of transient hydraulic conditions at Ft. Wainwright.

6. MODEL SIMULATIONS

After MODFLOW was used to calculate ground water fluxes in the system for 1995 through 1998, the fluxes were used to define the boundaries of the BIOMOC model. The BIOMOC model was tested by comparing the simulated transport of a conservative solute with data collected in the field. The conservative solute is alkalinity as $CaCO_3$. Alkalinity measurements were taken periodically during spring and summer 1997. In 1997, bank recharge only occurred during spring snow-melt. Figure 12 shows the change in alkalinity with depth, twenty feet from the Chena River observed in the field. Changes in alkalinity were not detected beyond 20 ft. from the river. The changes in alkalinity were used to determine the percentage of ground water replaced by surface water. Hinzman et al. (in review) determined 64 to 68 percent of ground water was replaced by surface water at 22.5 feet below the ground surface at 20 ft. from the river during the bank recharge event. However, alkalinity measurements were not taken during peak river stage, but a few days after. Figure 13 shows the simulated change in alkalinity during the 1997 spring melt bank recharge event.

The alkalinity of Chena River water varies from 56 to 96 mg/l throughout the season. Field data show rapid changes in alkalinity occur just before break-up when snow melt is being added to stream discharge. An average value of 76 mg/l is used in the simulation.

The percentage of mixing between ground water and surface water determined by the simulation is higher when compared to field observations. The simulation shows approximately 80 percent of ground water being replaced by surface water at 21.62 feet

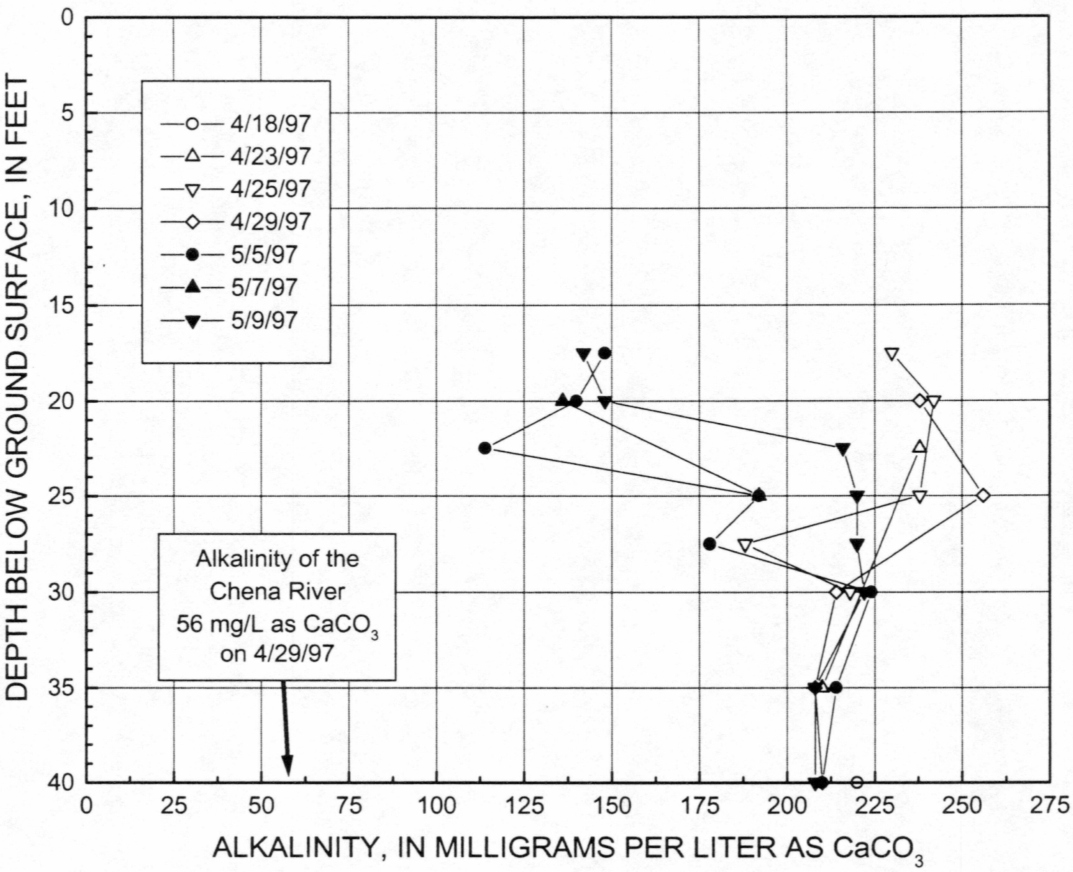


Figure 12. Alkalinity versus depth at FWM7331, April 18 through May 9, 1997.

below the ground surface. Observed changes in field alkalinity data vary considerably with depth. In contrast, simulated changes in alkalinity do not vary considerably with depth . The simulation shows a larger vertical extent of mixing than field measurements. The greatest change in simulated alkalinity occurs at 22 ft. below the ground surface. The large volume of simulated water discharging and recharging from the river results in much greater solute fluxes close to the river.

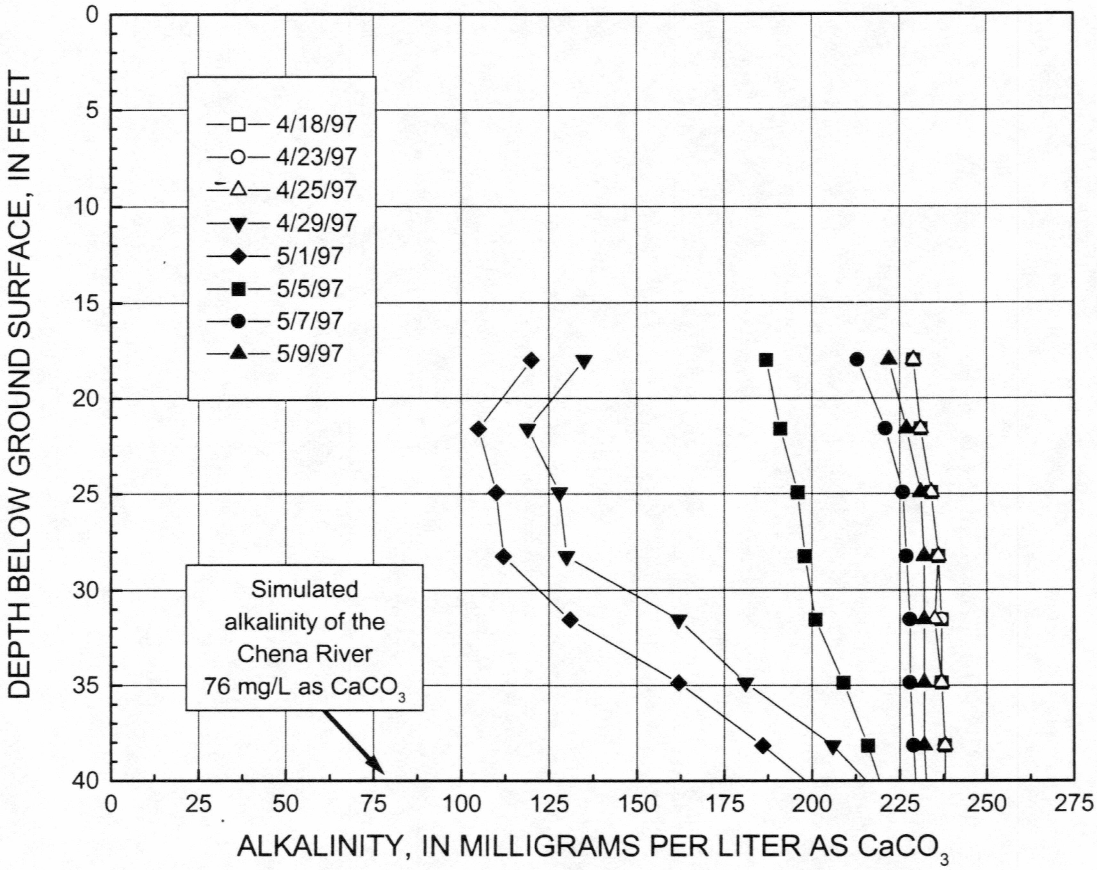


Figure 13. Simulated alkalinity versus depth 20 ft. from the river.

Velocity distribution close to the river greatly affects the solute transport. The simulation's temporal response to the bank recharge event is faster than that observed in the field. The simulation attenuates the bank recharge event approximately 3 to 4 days before field data shows. This is due to dramatic increases in hydraulic gradient close to the river caused by large pumping/injection rates at nodes defining the river resulting in high ground water velocities.

7. MODEL LIMITATIONS

The constraints and assumptions of the BIOMOC and MODFLOW two-dimensional models significantly affect solute transport analyses when interpreting small-scale effects of transient hydrology. The cross-sectional MODFLOW model utilizes time-variant specified head boundaries (1998). The no-flow boundary defining the model grid below the river forces the entire ground water flow regime to discharge into the cell simulating the Chena River. The use of specified-head boundaries with this condition will not affect the water levels or river stage in the simulation, however an unlimited volume of water can discharge and recharge from the river.

Accurate solute transport analyses require precise water budget calculations. The concentration of contaminants is sensitive to ground water fluxes. The transport of contaminants depends on the ground water velocity. The cross-sectional MODFLOW model assumes there is no ground water flow beneath the Chena River. When fluxes calculated by the MODFLOW model were used to define the BIOMOC model boundaries, high ground water velocities result. This supports estimates that a component of the ground water flow must be flowing beneath the river. The amount of water flowing beneath versus discharging into the Chena River is unknown.

The position and type of boundaries in the BIOMOC model limit transport and biodegradation simulations. The north end of The cross-sectional MODFLOW model is defined by the Chena River which is a hydrologic source and sink. Field data for the area directly to the north of the Chena River at the study site is not available. When prescribed-flux boundaries, which use pumping/injection wells, are used directly adjacent to no-flow boundaries, draw-down levels are falsely large. Thus ground water velocities are high near the boundaries. Farther away from the boundaries, ground water velocities approach correct values, but are still high. The BIOMOC model is stable, however calculations of transport and biodegradation directly adjacent to the river are erroneous. In order to accurately simulate transport and biodegradation of solutes utilizing this modeling approach, a component of the ground water must flow beneath the simulated Chena River so that the correct ground water discharge rate into the river occurs.

Losses of benzene contamination due to processes other than anaerobic biodegradation are not accounted for in this simulation. Other natural attenuation processes such as volatilization, aerobic biodegradation at the water table, and chemical decay are not included in the BIOMOC model. Low concentrations of dissolved oxygen have been reported in the Chena Alluvium aquifer at Ft. Wainwright (Braddock et al. 1998) suggesting in-situ conditions could support aerobic microbes. However, limited data are available showing aerobic and anaerobic biodegradation potential measured in the lab is actually realized in the field. Model simulations provided in this thesis utilize conservative biodegradation parameters. Improved simulations are possible when more microbiological field data becomes available. The addition of more biodegradation, sorption, and chemical processes would significantly affect the results of these BIOMOC simulations.

8. RESULTS AND DISCUSSION

BIOMOC was used to interpret the effects of transient hydraulic conditions on transport and biodegradation of benzene contamination in the OU5 area at Ft. Wainwright from 1995 to 1998. The benzene biodegradation rate used in the model was 0.0002 d^{-1} (Borden et al. 1997). This is the average rate of anaerobic degradation over the entire simulated benzene plume. Utilizing this rate, the simulation shows biodegradation of benzene to be practically nonexistent.

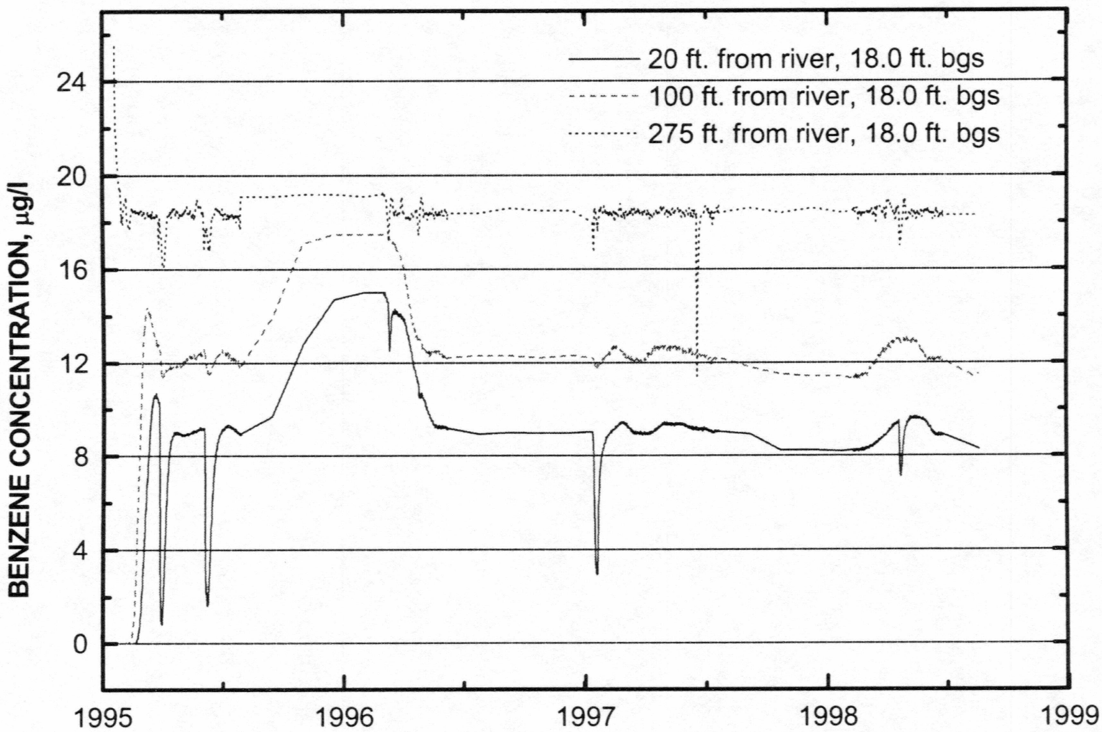


Figure 14. Simulated concentrations of benzene at three different distances from the river.

Approximately 0.003 % of the total benzene entering the ground water is biodegraded, 0.6 % is adsorbed onto soil, and the remainder exits the system into the river. Reactions in the vadose zone are not modeled. Vadose zone activities could significantly affect the rate of biodegradation and adsorbtion of benzene in the system.

Dispersion and advection affect the benzene concentration distribution. In the simulation, ground water discharging into the Chena River has benzene concentrations ranging from 2 to 8 μg/l. The portion of the simulation representing 1995 shows significant contaminant transport away from the river during high river stage events (Figure 14). High river stage events resulting in bank recharge throughout the simulation are shown by the changes in benzene concentrations. When bank recharge occurs, a sharp decrease in benzene concentration occurs as surface water is replacing contaminated ground water. The benzene concentrations then return to the levels they were prior to the event. The duration of each bank recharge event determines to what extent the benzene is retarded before discharging into the river.

During the winter recession of 1995 to 1996, benzene concentrations gradually increase until the 1996 portion of the simulation. Benzene concentrations then decrease and stabilize for the remainder of the simulation, with instantaneous changes due to minor bank recharge events. The simulation shows that reversals in hydraulic gradient during peak river stage events increases the time required for contaminants to discharge into the river. The rising and falling of the water table creates a smear zone in the unsaturated zone of the aquifer material, which is not included in the simulation. This could significantly affect the rate of biodegradation and contaminant transport in the natural system by moving the contamination into an area with sufficient oxygen for aerobic bacteria to utilize benzene as a carbon source.

It is possible that large hydrologic events, similar to those seen in 1995, in succession could change the amount of dissolved oxygen available in the system by the in-flux of fresh surface water and movement of the water table into the unsaturated zone. This would result in aerobic biodegradation of benzene which is much more effective than anaerobic biodegradation. However, insufficient data is available to distinguish between geochemical and microbiological utilization of dissolved oxygen during bank recharge events at Ft. Wainwright.

Figure 15 shows profiles of benzene concentration along the model cross section for selected times during the simulation. The only time benzene concentrations are significantly different is during the winter recession of 1995 to 1996 (simulation days 200 to 395, 10/30/95 to 5/15/96). The simulation indicates that essentially all of the benzene in the system eventually discharges into the Chena River at a concentration of 2 to 8 µg/l.

The constraints placed on the model limit the ability to precisely describe the natural system. The use of specified head boundaries in the MODFLOW model increases the instability of the BIOMOC model because simulated discharge rates into the Chena River are too great. However, the BIOMOC model does converge. Mass balance residual calculations done by BIOMOC show a 10 % error in the chemical mass balance.

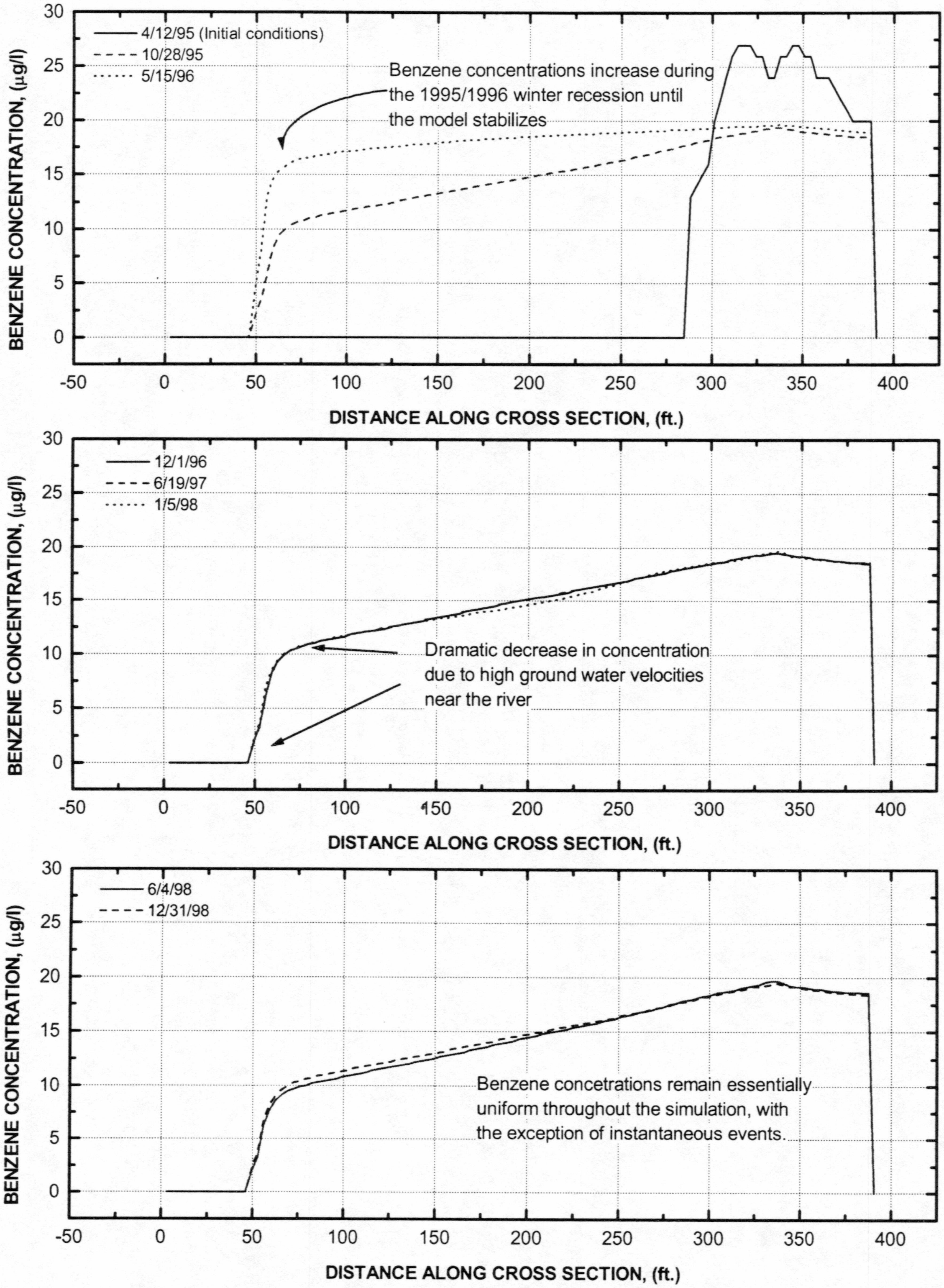


Figure 15. Profile of benzene concentration along model cross section throughout the simulation.

Figure 16 shows a comparison between field measured and simulated benzene concentrations. Field measurements show that benzene does not discharge into the Chena River. By the end of the simulation, benzene concentrations are less than field measurements at the up-gradient end of the cross-section, and greater than field measurements at the down-gradient end of the cross-section. The simulation follows the general trend of decreasing benzene concentrations with decreasing distance from the river.

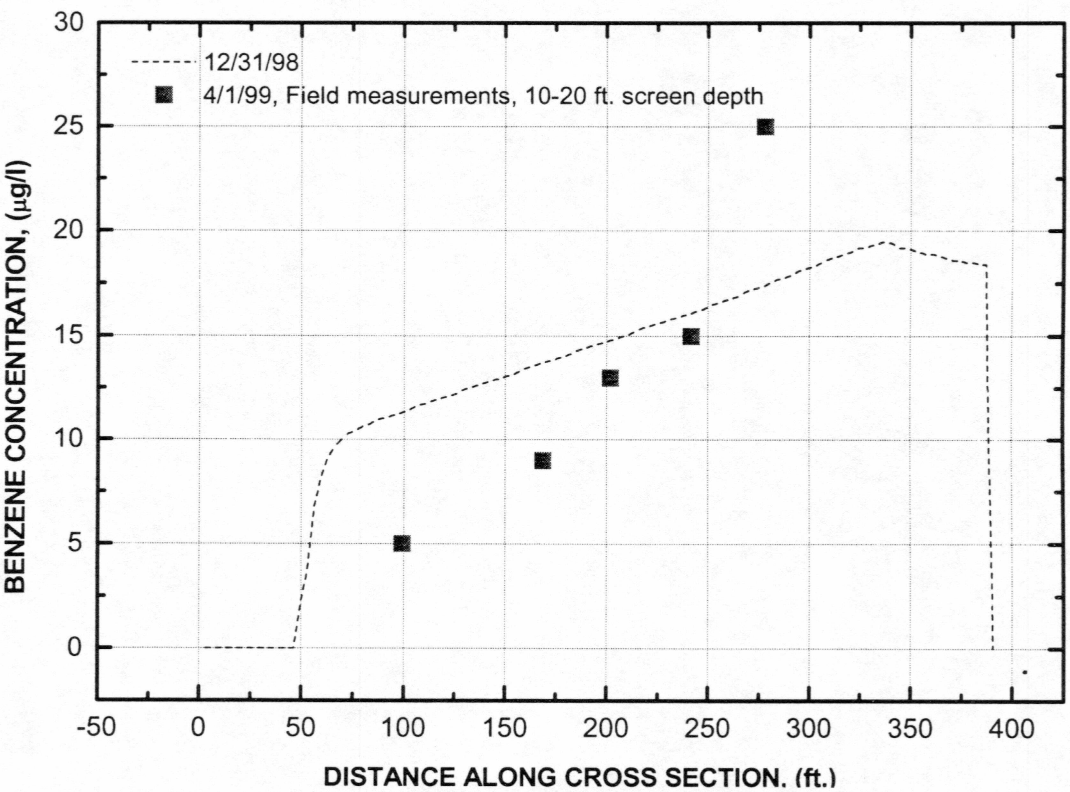


Figure 16. Comparison of the BIOMOC simulated benzene distribution in layer 2 (18 ft. below ground surface) and the measured benzene distribution (10-20 ft. screen depth).

Field measurements indicate that processes not accounted for in the BIOMOC model simulations affect the benzene transport. Natural attenuation processes such as volatilization, aerobic biodegradation, and chemical decay are not included in this BIOMOC simulation. The addition of more biodegradation processes and losses due to chemical processes into this BIOMOC model simulation would significantly affect the simulated benzene distribution.

9. SUMMARY AND CONCLUSIONS

The BIOMOC model shows anaerobic biodegradation and adsorbtion of benzene in the saturated zone at Ft. Wainwright are negligible close to the river. The simulation suggests that the benzene plume ultimately discharges into the river. Dispersion and advection affect the benzene concentration distribution in the system, causing the concentration of benzene to decrease from 20 μg/l at 300 ft. from the river to 2 to 8 μg/l directly adjacent to the river. Field data collected by the CH2M Hill (1999) does not support this finding. Field measurements show benzene concentrations to be relatively stable and not discharging into the river. The simulation shows instantaneous changes in hydraulic gradient directly adjacent to the river affect the ultimate fate of benzene contamination by retarding contaminant transport to the river. The only period with significant changes in river stage in this study are during 1995. The stage levels of the Chena River from 1996 to 1998 were uncharacteristically low. Hydrologic years similar to 1995 in succession could affect benzene concentrations significantly.

The average ground water velocity calculated by the model is at least three times greater than the reported value for the Ft. Wainwright area (Lawson, personal comm.). This causes the simulated benzene plume to discharge into the river prematurely. Dispersion, advection, and biodegradation would affect the concentration of benzene in the system to a greater extent if the simulated ground water velocities were slower (Burns et al. 1999).

Simulated benzene concentrations discharging into the Chena River are greater than field measurements show (CH2M Hill, 1999). However, processes occurring in the unsaturated zone are not simulated and could greatly affect the concentration of benzene discharging into the river. Processes not accounted for in this model are affecting benzene concentrations before discharging into the river.

A few of the complexities of modeling solute transport and biodegradation during transient hydraulic conditions have been introduced in this report. Bank recharge events must be continuously monitored and complex modeling efforts are required to precisely and accurately describe the system surrounding the Chena River.

10. RECOMMENDATIONS

It is recommended that contaminant transport modeling be continued in the OU5 area on Ft Wainwright. The complexity of the hydrologic, geochemical, and microbiological systems requires robust modeling approaches. Three-dimensional analysis is highly recommended. This report provides an initial understanding to modeling the small-scale effects of instantaneous hydrologic events on benzene transport and biodegradation in ground water. Further analysis of ground water discharge rates into the Chena River is needed to precisely describe the hydrology of the system. This will greatly affect two-dimensional and three-dimensional analyses of interactions between the Chena River and the alluvial aquifer.

BIOMOC input parameters for biodegradation and chemical decay can be modified. When sufficient field data become available concerning the processes governing the ultimate fate of benzene in the OU5 area, the BIOMOC model simulations can be modified to reflect those findings.

Modeling contaminant transport in the unsaturated zone is needed. The affects of contaminant smearing in the vadose zone due to the rising and falling of the water table are unknown. The amount of aerobic versus anaerobic biodegradation of benzene in the saturated and unsaturated zones is unknown. Factors controlling chemical degradation are unknown. Additional modeling efforts and in-situ process studies are needed to fully understand the fate of contaminants close to the Chena River.

11. REFERENCES

American Society for Testing and Materials (ASTM). 1997a. Standard practice for design and installation of ground water monitoring wells in aquifers: Standard D5092-90, 04.09: West Conshohocken.

American Society for Testing and Materials (ASTM). 1997b. Standard test method for determining subsurface liquid levels in a borehole or monitoring well: Standard D4750-87 (1993), 04.08: West Conshohocken, 6 p.

Anderson, G.S. 1970. Hydrologic reconnaissance of the Tanana Basin, central Alaska: U.S. Geological Survey Hydrologic Investigations Atlas HA-319, 4 sheets.

Andreasen, G.E., Wahrhaftig, C., and Zietz, I. 1964. Aeromagnetic reconnaissance of the east-central Tanana lowland: U.S. Geological Survey Geophysical Investigations Map GP-447, 3 p., 1 plate.

Borden, R.C., Daniel, R.A., LeBrun IV, L.E., Davis, C.W. 1997. Intrinsic Biodegradation of MTBE and BTEX in a Gasoline Contaminated Aquifer. Water Resources Research, Vol. 33, No. 5, p. 1105-1115.

Borden, R.C., Hunt, M.J., Shafer, M.A., Barlaz, M.B. 1997. Anaerobic Biodegradation of BTEX in Aquifer Material: Environmental Protection Agency Environmental Research Brief. EPA/600/S-97/003.

Braddock, J.F., Catterall, P., Richmond, S.A. 1998. Assessment of the potential for biodegradation of petroleum hydrocarbons in the Railroad Industrial Area, Fairbanks, Alaska, 1993-1994: U.S. Geological Survey Open-File Report 98-287, 10 p.

Braddock, J.F. 2000. Personal communication, April 3. Topic: Anaerobic biodegradation parameters at Ft. Wainwright.

Burns, S.B., Hinzman, L.D., Lilly, M.R. 1999. BIOMOC Simulation of Benzene Transport and Biodegradation During Transient Hydrologic Conditions: A Poster Presentation, 1999 AAAS Conference, Denali, Alaska; University of Alaska Fairbanks – Water and Environmental Research Center, 2 p.

CH2M Hill, 1997. Groundwater Modeling Building 1060, Delivery Order 11, Ft. Wainwright, Alaska. [Contract No. DACA85-95-D-0015]

CH2M Hill, 1999. Spring 1999 Groundwater Sampling East Quartermaster's Fueling System, Delivery Order 14, Ft. Wainwright, Alaska. [Contract No. DACA85-95-D-0015]

Essaid, H.I., Bekins, B.A., 1997. BIOMOC A Multispecies Solute- Transport Model with Biodegradation, U.S.G.S., Water-Resources Investigations Report 97-4022, 78 p.

Glass, R.L., Lilly, M.R., and Meyer, D.F. 1996. Ground-water levels in an alluvial plain between the Tanana and Chena Rivers near Fairbanks, Alaska, 1986-93: U.S. Geological Survey Water-Resources Investigations Report 96-4060, 39 p.

Harding Lawson Associates, 1995, Draft final management plan, operable unit 5, remedial investigation/feasibility study, Fort Wainwright, Alaska Draft, April, 1995: Anchorage, Alaska, prepared for the U.S. Army Corps of Engineers, Alaska District, variously paged [contract no. DACA85-94-D-0008, delivery order no. 0004]

Heimann, D.C., Richards, J.M., and Wilkison, D.H. 1997. Agricultural chemicals in alluvial aquifers in Missouri after the 1993 flood: Journal of Environmental Quality, v. 26, no. 2, p. 361-371.

Hinzman, L.D., Wegner, M.A., Lilly, M.R. in review. Hydrologic Investigations of Ground-water and Surface-water Interactions in Subarctic Alaska: submitted to Nordic Hydrology, 31 p.

Lawson, D.E., Arcone, S.A., Strasser, J.C., Delaney, A., Williams, C., and Albert, D. 1993. Geological and geophysical analyses of permafrost and ground water conditions, Fort Wainwright, Alaska—1993 progress report: Hanover, New Hampshire, U.S. Army Cold Regions Research and Engineering Laboratory.

Lawson, D.E., Strasser, J.C., and Davi, J.M. 1994. Geological and geophysical investigations of the hydrogeology of operable unit 3 [Fort Wainwright, Alaska]—Interim draft report: Hanover, New Hampshire, U.S. Army Cold Regions Research and Engineering Laboratory.

Lawson, Peter. 2000. Personal communication, February 3. Topic: Chena River under-flow and ground water velocity at Ft. Wainwright.

Lilly, M.R., McCarthy, K.A., Kriegler, A.T., Vohden, J., and Burno, G.E. 1996. Compilation and preliminary interpretation of hydrologic and water quality data from the Railroad Industrial Area, Fairbanks, Alaska, 1993-94: U.S. Geological Survey Water- Resources Investigation Report 96-4049, 75 p.

McCarthy, K.A., Lilly, M.R., Braddock, J.F., Hinzman, L.D. 1998. Natural Attenuation of Chlorinated-Hydrocarbon Contamination at Fort Wainwright, Alaska: A Hydrogeochemical and Microbiological Investigation Workplan; U.S. Geologic Survey Open-File Report 98-198, 49 p.

Nakanishi, A.S., Lilly, M.R. 1998. Estimate of aquifer properties by numerically simulating ground-water/surface-water interactions in cross section at Fort Wainwright, Alaska: U.S. Geological Survey Water-Resources Investigations Report 98-4088, 35 p.

Nelson, G.L. 1978. Hydrologic information for land-use planning, Fairbanks vicinity, Alaska: U.S. Geological Survey Open-File Report 78-959, 47 p.

Newberry, R.J., Bundtzen, T.K., Clautice, K.H., Compellick, R.A., Douglas T., Laird, G.M., Liss, S.A., Pinney, D.S., Reifenstuhl, R.R., and Solie, D.N. 1996. Preliminary geologic map of the Fairbanks mining district, Alaska: Alaska Division of Geological and Geophysical Surveys, Public Data File 96-16, 2 sheets.

Péwé, T.L. 1958. Geology of the Faribanks (D-2) quadrangle, Alaska: U.S. Geological Survey Map GQ-110.

Péwé, T.L., Bell, J.W., Forbes, R.B., and Weber, F.R. 1976. Map showing the distribution of permafrost in the Fairbanks D-2 SE quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-669-A.

Péwé, T.L. and Bell, J.W., Forbes, R.B., and Weber, F.R. 1976. Geologic map of the Fairbanks D-2 SE quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-942. Scale, 1:24000.

Phelps, C.D, Kazumi, J., Lily, Y.Y., 1996. Anaerobic Degradation of Benzene in BTX mixtures dependent on sulfate reduction. FEMS Microbiology Letters 145 p. 433-437.

Plumb, E.W., and Lilly, M.R. 1996. Snow-depth and water-equivalent data for the Fairbanks area, Alaska, spring 1195: U.S. Geological Survey Open-File Report 96-414, 16 p.

Robinson, M.S., Smith, T.E., and Metz, P.A. 1990. Bedrock geology of the Fairbanks mining district: Alaska Division of Geological and Geophysical Surveys, Professional Report 106, 2 sheets.

Rust, B.R. 1978. "Depositional models for braided alluvium." In Miall, A.D., ed., *Fluvial Sedimentology*: Canadian Society of Petroleum Geology Memoir 5, p. 605-625.

Squillace, P.J., Caldwell, J.P., Schulmeyer, P.M., and Harvey, C.A. 1996. Movement of agricultural chemicals between surface water and ground water, lower Cedar River Basin, Iowa: U.S. Geological Survey Water-Supply Paper 2448, 59 p.

Squillace, P.J. 1996. Observed and simulated movement of bank-storage water: Ground Water, v. 34, no. 1, p. 121-134.

Squillace, P.J., Burkart, M.R., and Simpkins, W.W. 1997. Infiltration of atrazine and metabolites from a stream to an alluvial aquifer: Journal of the American Water Resources Association, v. 33, no. 1, p. 89-95.

U.S. Coast and Geodetic Survey. 1996. Vertical control datum: U.S. Dept. of Commerce, Environmental Sciences Services Administration, September, 26 p.

Wegner, M.A. 1998. Transient Groundwater and Surface-water Interactions at Ft. Wainwright, Alaska: M.S. thesis, University of Alaska Fairbanks.

White, D.M. 2000. Personal communication, January 20. Topic: Anaerobic biodegradation parameters.

12. APPENDIX

Regression analysis of Chena River and monitoring well FWM5756 1995 data to determine water levels at FWM5756 for 1996 through 1998. All calculations performed using Origin 5.0.